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Development of a Sorbent Distribution and Recovery System

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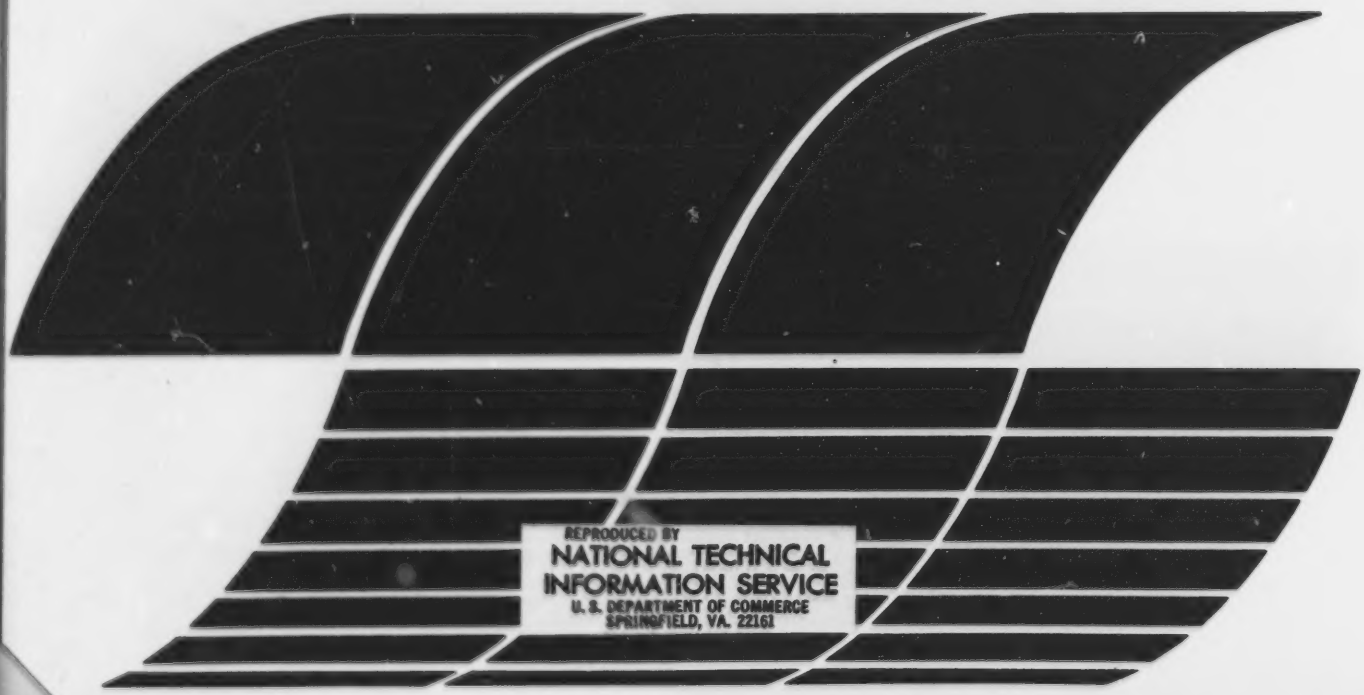

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The sorbent is transported and distributed over the water surface by means of a pneumatic broadcaster. An inclined, open wire mesh belt conveyor is used to remove the saturated sorbent from the water. The recovered oil and water is removed from the sorbent by squeezing in a converging belt press or regenerator. After regeneration, the foam is reapplied to the oil slick. The foam can be reused for a great many cycles.

Tests of the system, using both diesel fuel and lubricating oil, were conducted at EPA's OHMSETT facility. The sweep speeds ranged up to 5 knots in both calm water and waves. Oil collection rates of 10.5 m^3/h were achieved. The oil content of the recovered liquid varied from 38% to 79%.

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DEVELOPMENT OF A SORBENT DISTRIBUTION AND RECOVERY SYSTEM

by

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report describes the development and testing of a versatile system for collecting spilled oil from the water's surface. The system described makes use of particles of reticulated polyurethane foam which are both olephilic and hydrophobic. Because of these properties, the particles are able to preferentially absorb the oil from the slick. In addition to the sorbent foam, the system includes equipment for storing and distributing the foam, and for recovering the oil from the foam. The results of this report will be useful both to those responsible for the operation of the prototype system and to others working in the field of waterborne oil spill recovery. Further information may be obtained through the Resource Extraction and Handling Division, Oil & Hazardous Materials Spills Branch in Edison, New Jersey.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

This report describes the design, fabrication, and test of a prototype system for the recovery of spilled oil from the surface of river, estuarine, and harbor waters. The system utilizes an open cell polyurethane foam in small cubes to absorb the floating oil. The system is highly mobile and can be transported in two pickup trucks.

The sorbent is transported and distributed over the water surface by means of a pneumatic broadcaster. An inclined, open wire mesh belt conveyor is used to remove the saturated sorbent from the water. The recovered oil and water is removed from the sorbent by squeezing in a converging belt press or regenerator. After regeneration, the foam is reapplied to the oil slick. The foam can be reused for a great many cycles.

Tests of the system, using both diesel fuel and lubricating oil, were conducted at EPA's OHMSETT test tank. The sweep speeds ranged up to 5 knots in both calm water and waves. Oil collection rates of 10.5 m^3/h were achieved. The oil content of the recovered liquid varied from 38% to 79%.

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METRIC CONVERSION FACTORS

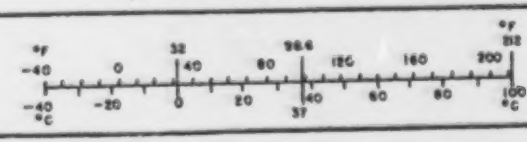
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



LIST OF ABBREVIATION AND SYMBOLS

ABBREVIATION

r	--correlation coefficient

SYMBOLS

E	--throughput efficiency
F	--oil fraction
R	--sorbent broadcast rate
T	--oil slick thickness
U	--viscosity
V	--velocity
VE	--volumetric efficiency

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Hydronautics, Incorporated, developed the sorbent broadcaster under the direction of William T. Lindemuth.

Garth D. Gumtz of Morris Knowles, Inc., designed the sorbent regenerator.

The Office of Research and Development, U. S. Environmental Protection Agency, supported this project. J. Stephen Dorrler was project officer.

SECTION 1

INTRODUCTION

Spilled oil and other liquid contaminants with specific gravities less than 1.0 tend to float on water. Numerous devices have been developed for collecting spilled oil. Most use a skimming device to pick up a thin slice of oil from the top of the water column. The performance of these devices tends to be seriously degraded by waves and currents. Collection of floating oil by means of a sorbent material, such as straw, which is then mechanically removed from the water is another frequently used technique. The sorbent approach is less affected by waves and current, but has the disadvantages of producing large amounts of oily sorbent, which is difficult to dispose of, and of presenting logistical problems in supplying the volume of raw sorbent.

In an effort to foster the development of new techniques for oil recovery, the U. S. Environmental Protection Agency (EPA) funded the development of an oil recovery system employing reuseable sorbent material. Reuseable sorbent retains the advantages of other sorbent techniques, being less sensitive to wave and current action, and also significantly reduces the sorbent supply and disposal problems. Further, the oil can be recovered in a useful form.

The objectives of this program were to design, build, and test a reuseable sorbent system for recovering spilled oil from the surface of river, estuarine, and harbor waters. The system was based on the results of previous EPA contracts. The system was to be easily transportable in standard pickup trucks. Each system unit was to be individually powered and operated either as part of a continuous process or independently. Each unit, other than the sorbent regenerator, was to be manually transportable over rough terrain. The complete system was to be operable from vessels of opportunity or from a combination of one or more small boats and a dock or shore.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

Of necessity, the OHMSETT testing of the prototype sorbent oil recovery system was limited in its extent. Tests were limited to a small number of speeds, wave conditions, and slick thicknesses and, because of physical limitations, testing was not done in a continuous mode. Still, the system demonstrated that the concept is sound and that the prototype equipment is a useful tool in the cleanup of spilled oils and selected floating hazardous substances, at a minimum, for the range of conditions under which it was tested. These conditions were; relative velocities of up to 5 knots; waves up to 0.3 in height; and slick thicknesses from 0.24 mm to 0.84 mm.

Under the best conditions the system was able to collect virtually all of the oil encountered. Better than 40 percent of the oil encountered was collected even under the most adverse conditions of high speed and waves.

In the best test case, oil was collected at a rate of 10.5 m^3/hr, from a 0.5 mm slick at a sweep speed of 2.5 knots with a sorbent distribution rate of 17.4 m^3/hr.

The recovery system is highly mobile, being transportable in only two pickup trucks. With the exception of the foam regenerator, all system elements can be transported manually over rough terrain.

Sorbent losses due to wind effects with wind velocities up to 15 knots are negligible. More significant foam losses occur due to waves washing over the containment boom. During the test program, the maximum losses occurred at 5-knot sweep speeds in 0.3-m breaking waves. These losses were less than 2%.

Regenerated foam densities were significantly higher than were predicted from prior laboratory tests. The design regenerated foam density was 140 kg/m^3 using a roller squeeze force of 7 N/mm. During testing, the regenerated foam density averaged 160 kg/m^3 using an average squeeze force of 16 N/mm. This probably resulted from oil clinging to the outside of the foam during squeezing and then being reabsorbed into foam when the

squeeze force was removed. During testing, the oil concentration varied from 38% to 79%. The recovered liquid was not highly emulsified and gravity separation of the oil and water was rapid.

Complete removal of all oil, or "sheen polishing," is not possible using recycled foam in this system because of oil remaining in the foam cubes after regeneration.

System throughput efficiency could be improved by operating with a sorbent logjam in front of the harvester. This would increase contact time which, as the test results indicate, would increase throughput efficiency. Operating with a logjam was not done during the test program, in order to reduce the number of test variables.

It is recommended that the system be operated on a variety of actual oil spills to gain additional performance information under more realistic conditions.

It is recommended that the system be operated in a continuous mode in order to prove its capabilities in this mode since physical limitations prevented testing in this mode at OHMSETT.

It is recommended that in order to improve the tracking of the regenerator upper squeeze belt and to eliminate the slippage between the belt and the drive roller, that standard drive roller lagging be applied in narrow strips with oil resistant adhesive and should be applied in a helical or chevron pattern from either end of the roller.

SECTION 3

MODES OF OPERATION

The two modes of operation of the sorbent oil recovery system are batch processing and continuous processing. The major difference between the two modes is that transfer conveyors are used in continuous processing. These conveyors carry the sorbent from harvester to regenerator, and from regenerator to broadcaster.

The following two scenarios illustrate these two modes of operation. The first scenario is for batch processing as conducted on the bank of a stream where a spill has occurred. In the second, the system has been mounted on a barge to recover an oil spill from harbor waters.

BATCH PROCESSING

An accidental spill has occurred in a small stream. The cleanup crew of 6 or 8 transfers the entire sorbent oil recovery system onto two available pickup trucks. The regenerator nearly fills the back of one pickup, while the second transports the sorbent broadcaster, harvester, and power supplies.

The trucks are driven to within 15 m of the stream. The cleanup crew forms three teams, or crews, one to set up each major component (Figure 3.1).

One crew consisting of one or two people wheels the sorbent broadcaster over the rough terrain to the bank of the stream. The flexible duct is attached directly to the discharge of the blower, and the nozzle is clamped onto the other end of the duct. Once the fuel tank is filled, the broadcaster is ready for operation.

The other people of the cleanup crew, meanwhile, ready the sorbent harvester. It is offloaded from the truck and wheeled to the bank, downstream of the broadcaster. Assembly is rapid. The diverter plates are bolted onto the frame, the floats are attached, and the lower end is slipped into the water. The upper end of the harvester is supported on the uneven ground by the telescoping legs. These are adjusted until the conveyor reaches

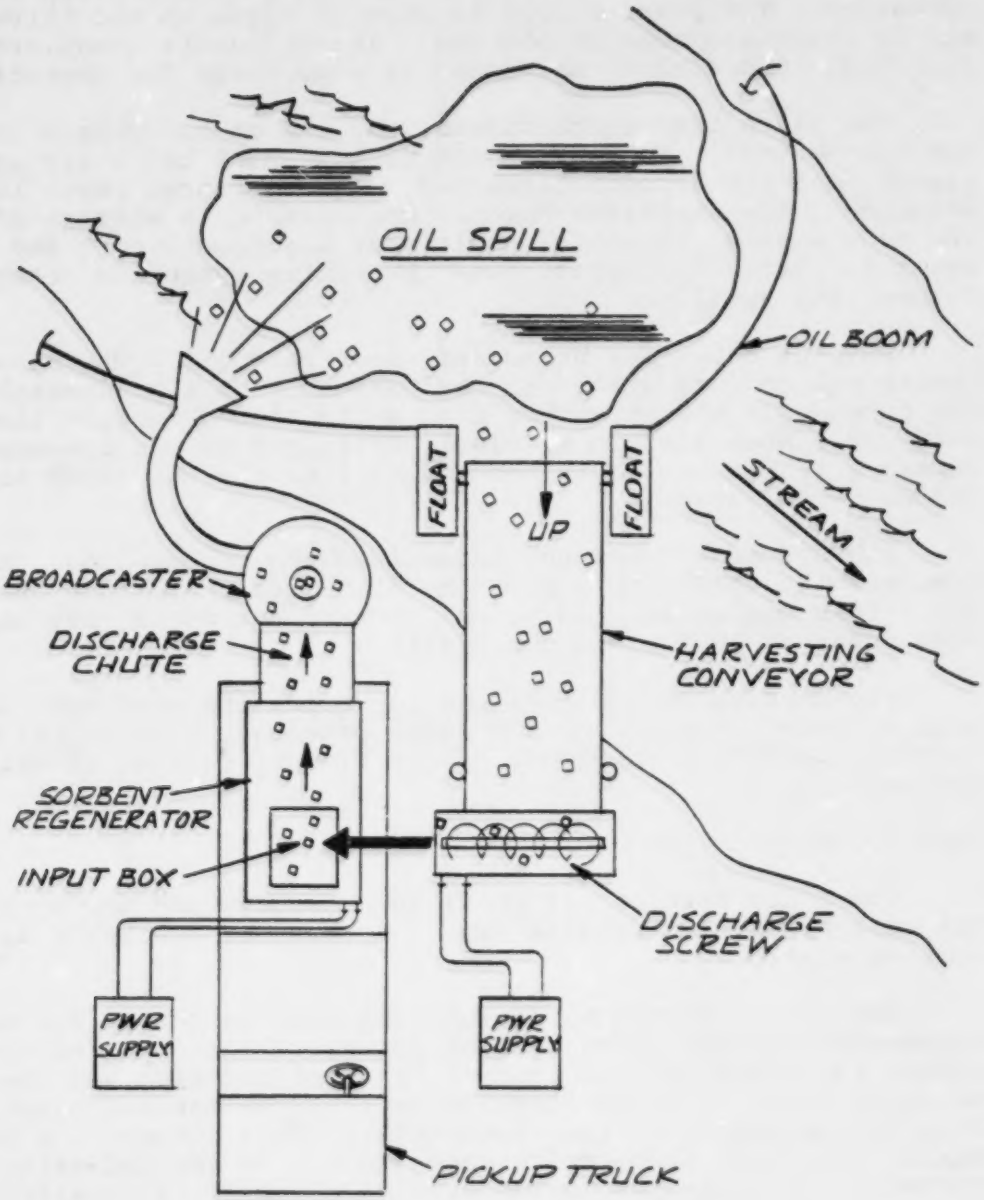


Figure 3.1. Sorbent oil recovery system deployed at a stream.

an angle of approximately 0.52 rad from horizontal. Another crew has brought the diverter boom and attaches it to the harvester's downstream diverter plate. The other end of the diverter boom is anchored upstream to herd the sorbent into the mouth of the harvester. The power supply is wheeled close to the harvester and is positioned out of the way. The hydraulic hoses are attached. The sorbent harvester is also ready for operation.

The third team which consists of one or two people readies the regenerator. They drive the pickup truck to fairly level ground near the sorbent harvester. The discharge chute is attached. The discharge hose is connected to a storage tank. The team wheels the power supply near the regenerator and connects the hydraulic hoses. Now the entire system is ready to recover the spill.

Sorbent cubes are broadcast into the spill. The cubes absorb oil and are guided to the harvester by the diverter boom. The cubes exit the harvester into a bin placed beneath the screw conveyor. When the bin is nearly full, one of the cleanup crew replaces it with an empty one and carries the saturated sorbent to the regenerator.

The operator feeds the cubes into the regenerator. Nearly free of oil, they tumble down the discharge chute into another bin. This bin is carried to the stream bank where they will once again be applied to the spill.

The members of the team not operating the equipment are used to carry bins of sorbent cubes between the three major components, providing an almost steady flow of sorbent around the system.

CONTINUOUS PROCESSING

There has been an oil spill in a harbor, and the sorbent oil recovery system will be used. A barge is available as the working platform.

The system is set up in much the same manner as for batch processing, except that transfer conveyors (not part of the system described in this report) replace the bins and the people to carry them. A screw conveyor carries the saturated sorbent from the harvester to the regenerator. This conveyor, a commercially available item, bolts onto the end of the harvester's screw conveyor. A belt-type conveyor, also commercially available, carries the oil-free cubes to the broadcaster. The use of conveyors to transport the sorbent allows operation of the system by a crew of 3 or 4 operators. The broadcaster's nozzle is mounted near the bow of the barge. The harvester is attached to the side of the hull. A diverter boom on one side, and the hull on the other, funnel the saturated sorbent into the harvester. The cubes

are lifted by the harvester belt and dropped into the screw conveyor, which takes them to the regenerator to be squeezed free of oil. To complete the cycle, the belt conveyor carries the squeezed sorbent back to the broadcaster.

SECTION 4

DEVELOPMENT PROGRAM

BACKGROUND

In June 1971, the U. S. Environmental Protection Agency (EPA) awarded five research contracts to evaluate the feasibility of the recovery of floating oil using reuseable foam sorbent material. The preliminary design of equipment to distribute, to harvest, and to remove the oil from the foam was included in the scope of these contracts. The complete results of these contracts are contained in references 1 through 5. In general, these reports concluded that such an oil recovery system was feasible, and they recommended the construction of a prototype system.

On October 1, 1974, the EPA awarded a contract to Seaward International, Inc., of Falls Church, Virginia, for the design, construction, and test of a sorbent oil recovery system. The system was to consist of the following component elements:

1. Reuseable foam sorbent
2. Sorbent broadcasting unit
3. Sorbent Harvesting unit
4. Oil-sorbent separator unit

DESIGN FEATURES

The sorbent distribution and recovery system allows rapid recovery of spilled oil with sorbent cubes that can be reused over 100 times, according to the manufacturer. As a result of separating the oil from the sorbent, disposal problems are kept to a minimum. During the OHMSETT test program, the same sorbent was used repeatedly with both oils and other hazardous materials during three weeks of testing. No perceptible change in the sorbent was noted during this period.

Due to the design of the system, moderate currents and waves have little influence on collection efficiency. This fact was substantiated during the test at OHMSETT.

Each system component has debris-handling features. On the harvesting conveyor, a cross brace is provided to block large debris. If small debris should jam the screw conveyor, it can be reversed to free the jam. The sorbent regenerator's rollers can be raised to pass debris. The broadcaster's duct easily disassembles for cleaning blockages. No testing, however, was done with debris present.

The system is highly mobile and maneuverable. The total system is capable of being transported entirely in two pickup trucks. All units other than the regenerator can be transported manually over rough terrain. The regenerator can be operated while in the bed of a pickup truck. Furthermore, each system component can be operated independently of the other components, since each is powered by a separate power supply. These capabilities were demonstrated during simulated field tests without oil.

COMPONENT SELECTION AND DESIGN

Reuseable Foam Sorbent

The earlier work conducted under the auspices of the EPA and described in References 2 and 4, optimized the sorbent material and configuration. It was concluded that the sorbent should be a high tensile (340 to 1400 kPa), industrial, open cell polyurethane foam with a density of 16 to 32 kg/m^3. For use with oil viscosity up to 1 Pa·s, a pore size of 3 pores/mm was recommended. A pore size of 1 pore/mm was recommended for oils with viscosity above 1 Pa·s. The optimum sorbent configuration was concluded to be cubes of 19 mm on an edge. The previous testing showed that this foam was capable of absorbing oil up to 30 times its weight. When squeezed, up to 90% of the oil could be removed from the foam leaving it as light as three times its original weight. When reused, the foam, prewetted with residual oil, had more absorbency than the virgin foam. Tests also showed that the foam could be recycled over 100 times with only slight loss of absorbency.

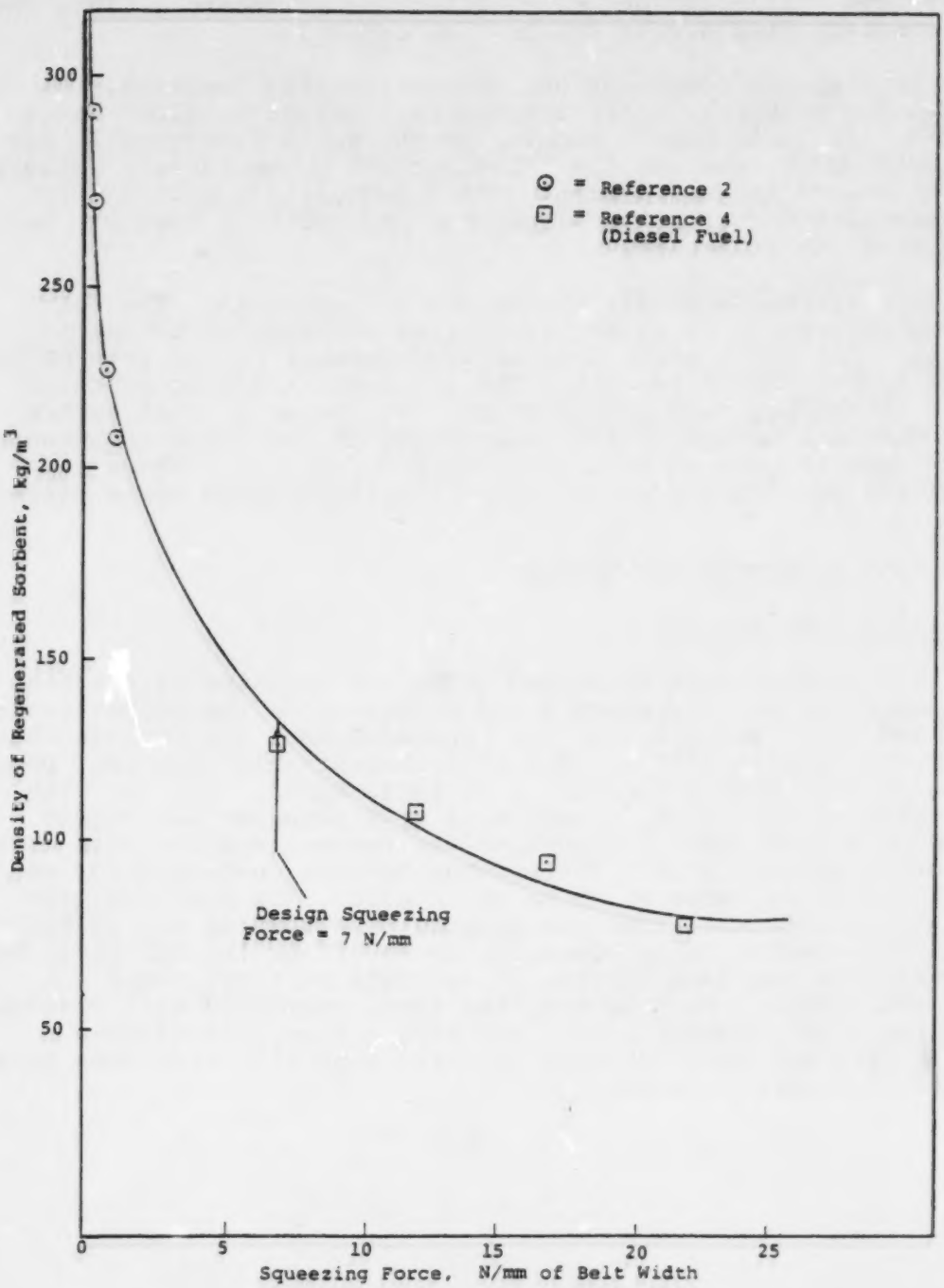


Figure 4.1. Regenerated sorbent density vs. squeezing force.

Following these recommendations, sorbent cubes of open-cell, reticulated, polyurethane foam were procured. The foam density is 32 kg/m^3, and each cube measures 19 mm on an edge. Pore size is 3 pores/mm.

Figure 4.1 is a plot of the regenerated sorbent density versus squeeze force that was derived from data in References 2 and 4. As shown in the figure, a design squeeze force of 7 N/mm was selected to give a reasonable low regenerated density at a moderate squeezing force level.

Sorbent Broadcasting Unit

Preliminary Design and Development of the Sorbent Broadcaster--

The sorbent broadcaster was developed and tested by Hydronautics, Inc., under a subcontract. Their report on the development of this work is the Appendix to this report.

Post-test Modifications to the Sorbent Broadcaster--

Two desirable modifications to the sorbent broadcaster became apparent during the testing at OHMSETT--a swivel in the discharge nozzle (Figure 4.2) would allow the operator to change the discharge direction easily, and an idler pulley would alleviate slippage problems and the tendency for the belts to come off during operation. Both of these modifications were incorporated prior to delivery of the system to the E.P.A.

The idler pulley is mounted on the broadcaster's base, and it engages the V-belts between the engine and the blower. The pulley adjusts to provide sufficient tension to prevent the V-belts from slipping. Another benefit of the third pulley is the prevention of the V-belts jumping off the pulleys.

As tested, the broadcaster nozzle was not free to turn about the axis of the flexible ducting. This made it awkward for the operator to broadcast the sorbent. Therefore, a swivel was added between the ducting and the nozzle. The design is simple: pins engaged in slots allow the nozzle to turn relative to the ducting, but the sorbent still encounters a smooth interior.

Final Design of the Sorbent Broadcaster--

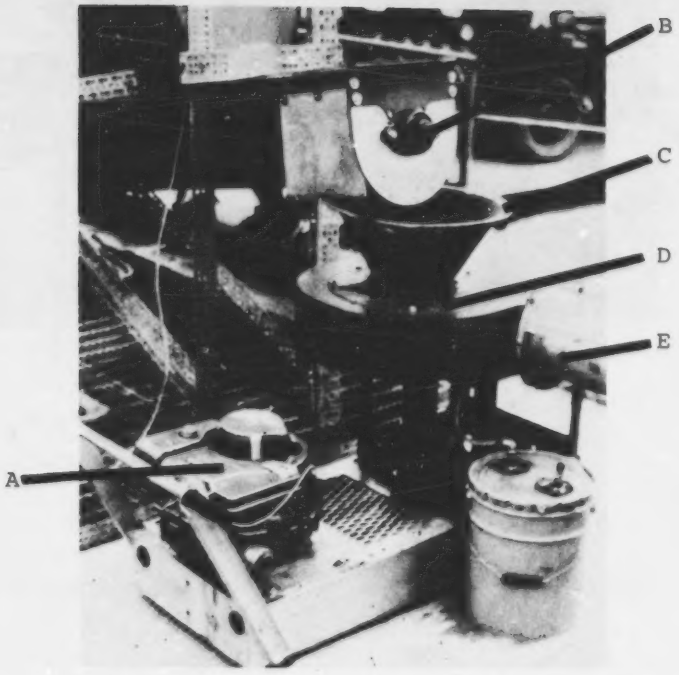
Principal characteristics of the sorbent broadcaster are listed in Table 4.1. Two men can transport this unit, since the heaviest component, the blower assembly, (Figure 4.3) has a mass of 80 kg. Its compact size is suitable for transportation in a pickup truck along with other system components.

An overall view of the sorbent broadcaster is shown in Figure 4.4, taken during the tests at OHMSETT. In this case, the sorbent cubes were fed to the blower from a feed hopper by a screw conveyor (at the right). The flexible ducting allows the operator to aim the cubes in any direction.

The blower assembly is constructed of commercially available parts. The blower itself is a Dayton "High-pressure blower" with a 340-mm open material handling wheel (Figure 4.5). It is powered by a 5.3-kW gasoline engine through a V-belt drive. The complete assembly is mounted on an integral frame with detachable wheels for easy deployment.

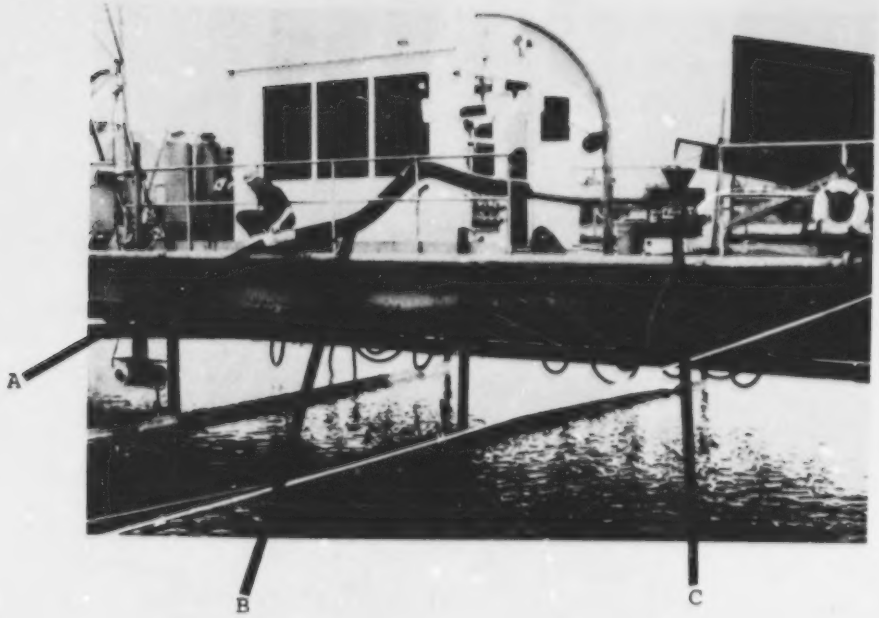
The sorbent cubes are transported from the blower to the nozzle through standard 8-inch sheetmetal ducting. The length and geometry of the ducting may be adjusted by using standard straight and adjustable elbow sections as required, although ducting lengths over 7.5 m is not recommended. The number and sharpness of the bends in the ducting should also be minimized for best performance. The last 1.8 m of the duct, between the rigid sheetmetal and the nozzle, is standard flexible ducting. The combination of the duct flexibility and the axial nozzle swivel permits the operator to aim the sorbent stream easily onto the oil.

Figure 4.2. Discharge nozzle of sorbent broadcaster.



A - engine
B - screw conveyor (not part of system)
C - inverted-cone hopper
D - blower
E - rigid duct

Figure 4.3. View of sorbent broadcaster's blower.



A - discharge nozzle
B - flexible duct
C - sorbent broadcaster

Figure 4.4. Overall view of sorbent broadcaster.

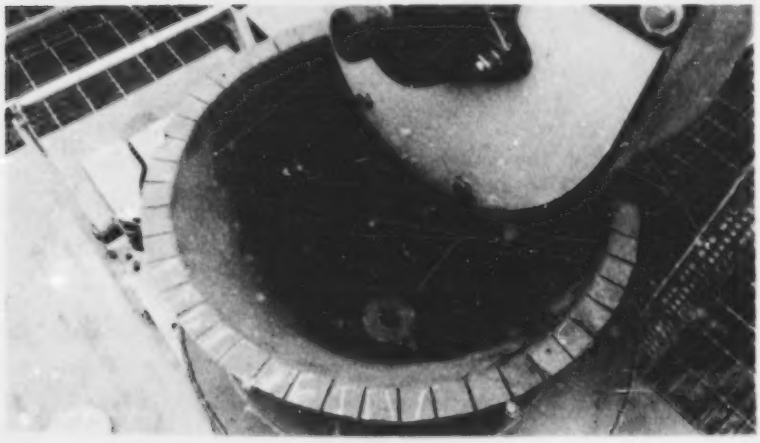


Figure 4.5. Open material handling wheel of broadcaster.

TABLE 4.1. CHARACTERISTICS OF THE SORBENT BROADCASTER

Capacity	1.1 kg/s
Length of Blower Assembly	1.43 m overall
Width of Blower Assembly	0.61 m overall
Height of Blower Assembly	0.99 m
Mass of blower assembly	80 kg
Mass of pipe, hose, and nozzle	23 kg
Blower type and size	Dayton "High-pressure blower" No. 4C131 with a 340 mm open material handling wheel
Blower speed (unloaded)	2900 rpm maximum
Duct type and size	200 mm diameter; 7.3 m long, including 1.8 m of flexible duct, with swiveling discharge nozzle
Power	5.2-kW gasoline engine with vertical shaft, driving the blower with V-belts
Frame	Contains engine and blower; integral handles and detachable wheels

Harvesting Conveyor

Preliminary Design of Harvesting Conveyor--

The preliminary design of the sorbent harvester was based on previous design work done (Reference 2). The preliminary design called for a small diesel engine to drive the belt through a variable speed drive, permitting the belt speed to be varied to match the relative velocity of the water. With a small diesel committed to the harvester, independent operation would be possible.

The belt was a round wire mesh of approximately 13 mm mesh. It was to meet the water surface at an angle of approximately 0.52 rad to prevent the foam cubes from tumbling.

Also included in the preliminary design for a vessel-mounted sorbent system was a transfer conveyor to collect the sorbent from the harvester and transport them to the regenerator. The belt was to have a speed range of 0.5 to 2.7 m/s and was to be driven by a right-angle drive from the harvester.

Development of Harvesting Conveyor--

At the outset of the development program, it was decided to stress the design goals of mobility and independent operation of each component of the sorbent system. Emphasis on these goals dictated much of the prototype design of the sorbent harvester.

In order to minimize individual component weights and to provide greater operating flexibility, the decision was made to utilize a gasoline engine, rather than a diesel engine, and to drive the harvester hydraulically. The hydraulic drive motor was small, lightweight, and was capable of providing a wide range of harvester belt speeds. A commercially available gasoline powered hydraulic power supply was selected. It was rated at 7.8 kW and had an output of 1.4 m^3/h at 10,000 kPa. This unit is lightweight and is easily transported since it is mounted on rubber tires. The gasoline engine is equipped with both an electric starter, and a manual backup for reliability and for use in explosive conditions.

The unit connected to the harvester motor by rubber hydraulic hoses, which provided flexibility in positioning the power supply and harvester during operations. The hoses allowed the power unit to be placed in a position remote from any explosive vapors. Thus, the flexibility provided by using a hydraulic drive system compensates for the lesser degree of safety of the gasoline engine as compared to a diesel engine.

The harvesting conveyor structure was fabricated in aluminum to keep its weight to a minimum. A stainless steel open mesh belt was used for the conveyor. The openings in this belt were selected so as to be large enough to permit water to flow easily through the mesh, at the same time preventing the foam cubes from falling through.

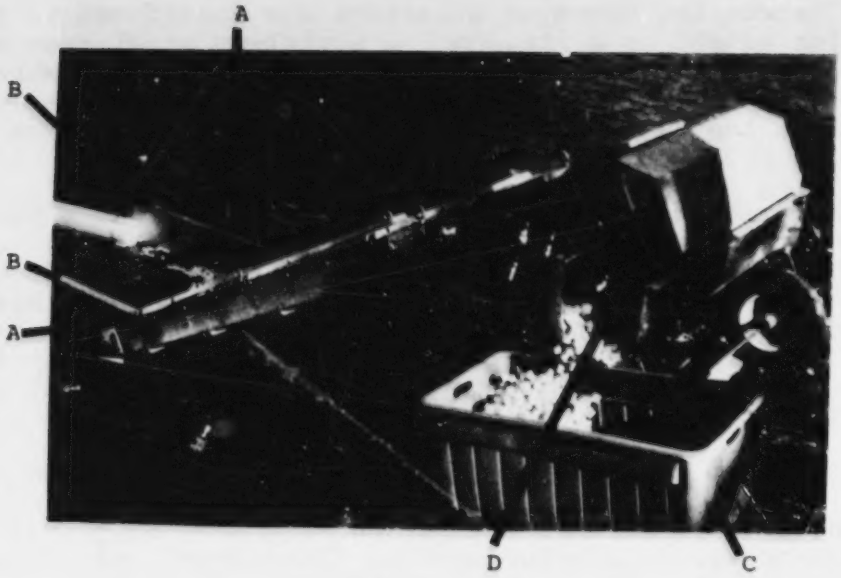
In order to keep the length of the harvester to a minimum, it was desirable to operate the conveyor at the steepest angle practical. Reference 2 indicated that an angle of 0.52 rad above the horizontal was about the steepest inclination possible without incurring tumbling of the cubes down the conveyor face; therefore, this angle was selected. A conveyor length of 3.7 m was selected. At the 0.52 rad angle, this provided for a vertical lift of about 1.5 m between the waterline and the sorbent discharge.

An aluminum channel was placed across the upper end of the conveyor to prevent large debris from being carried all the way up the conveyor. The sorbent cubes discharged from the conveyor belt into a 230-mm screw conveyor mounted transversely below the top of the conveyor belt. The conveyor screw, driven by its own hydraulic motor, was designed to be capable of being stopped and reversed to clear jams between the screw and conveyor trough. The screw speed was controlled by the hydraulic power unit engine speed. Provision was made to extend the screw conveyor length by the attachment of additional trough lengths and a longer screw. The screw conveyor is a standard, commercially available size.

During shop testing of the completed harvester unit, it was found that the inception of sorbent cube tumbling down the conveyor face commenced at about 0.4 rad inclination. To prevent this tumbling when operating at the design angle of 0.52 rad, flights were added to the conveyor belt. The flights were made by brazing spare conveyor belt wires at right angles to conveyor belt surface. The zig-zag shape of the wires provided 13 mm high flights across the belt face.

In order to support the conveyor, two pillow blocks were located under the side rails just above the center of gravity where the support shafts connected to foundations could be inserted. The lower end of the unit was supported by two articulated foam-filled pontoons mounted to the outsides of the frame at the water line. These pontoons allowed the conveyor to follow the undulating water surface.

For ease of overland transportation of the harvester, pneumatic tires were provided. They attached to the screw conveyor trough assembly at the upper end of the unit and were easily removable. (Figure 4.6.)



A - float
B - diverter plate
C - collection bin
D - screw conveyor

Figure 4.6. Harvesting conveyor at stream bank.

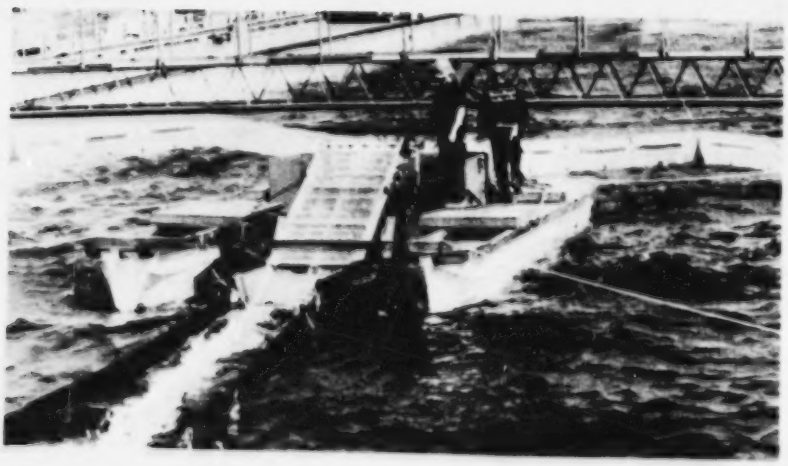


Figure 4.7. Harvesting conveyor on catamaran.

TABLE 4.2. CHARACTERISTICS OF THE HARVESTING CONVEYOR

Length	3.7 m overall at operating angle of 0.52 rad
Width	1.4 m overall
Height	2.2 m overall, at operating angle of 0.52 rad
Mass	140 kg
Conveyor width	0.91 m
Conveyor angle	0.52 rad from horizontal
Conveyor length	3.7 m
Belt speed	to 2 m/s
Belt type and size	heavy duty, stainless steel round-wire belt, 13 mm mesh
Belt drive	76-mm sprockets
Power	hydraulic pump (1.4 m^3/h at 10,000 kPa) driven by a 7.8-kW gasoline engine
Support	Integral support frame with wheels and with telescoping, adjustable legs; elastomer-covered foam floats support the lower end of the harvester in the water at its proper draft

Post-Test Modifications to the Harvesting Conveyor--

During testing at OHMSETT, two modifications to the harvester seem desirable--removing the expanded metal cover, and adding adjustable legs for support.

As tested, the harvester had an expanded metal cover over the belt, from the deflector plates at the lower end to near the drive sprockets (Figure 4.6). The cover prevented easy access to remove debris, and since it was evident that there would be little attendant danger, the expanded metal cover was removed.

When deployed from a vessel, the harvester was well supported as tested, but there was no provision to account for uneven ground if the harvester were to be deployed from a stream bank. Adjustable telescoping legs were added to the harvester with supports that rotated, allowing the legs to be adjusted in order to support the harvester belt at an angle of approximately 0.5 rad from horizontal.

Final Design of Harvesting Conveyor--

The characteristics of the sorbent harvester are listed in Table 4.2. Its size allows it to be transported in the back of a standard pickup truck. With a mass of 140 kg, two men can remove it from the truck and roll it over rough terrain to the spill site. Once there, telescoping, adjustable legs enable the operators to support the harvester at the desired angle of 0.52 rad.

Another mode of operation is shown in Figure 4.7. This photograph, taken during the tests at OHMSETT, shows the harvester mounted on a catamaran. The lower end is supported by two foam floats. Each float is covered with abrasion-resistant elastomer and is articulated, allowing the floats to conform to the water surface.

The conveyor itself is 0.91 m wide and 3.7 m long, permitting a vertical lift of 1.5 m from the water surface. Hydraulics power both the belt and the screw conveyor. Figure 4.6, taken before the post-test modifications were made, shows the belt's hydraulic motor and controls, as well as the screw conveyor with pneumatic wheels attached. The screw conveyor's separate hydraulic motor is mounted at the hidden end of the shaft.

Sprockets drive the belt directly. The belt speed is adjustable to 2 m/s, allowing the operators to control the speed as conditions dictate. If the belt is driven slowly, the sorbent cubes logjam in front of the harvester. This increases the contact time,which should improve recovery of the oil. During the test at OHMSETT, the belt was always driven fast enough to prevent logjamming, in order to allow the sorbent residence time to be easily determined, thus keeping the number of test parameters manageable.

Detachable aluminum side plates, which bolt onto the frame, channel the sorbent cubes into the harvester. These plates extend above and below the water surface to prevent escape of the sorbent, even in waves. The design of the plates also allows for the connection of diverter booms.

The power supply (Figure 4.8) is a separate component, adding further to mobility of the system. This unit is commercially available. The hydraulic pump is driven by a 7.8-kW gasoline engine, and it delivers 1.4 m^3/h at 10,000 kPa. Hydraulic hoses carry the fluid to the harvester, providing flexibility in placement of the power supply.

Sorbent Regenerator Unit

Preliminary Design of Sorbent Regenerator--

The preliminary design of the regenerator was based on the converging-belt sorbent regenerator of earlier EPA contracts (References 2 and 4). One major change of the preliminary design was to use springs to produce the compression load, another was to select a squeeze force of 7 N/mm, a compromise between the squeeze forces used in the two contracts referenced.

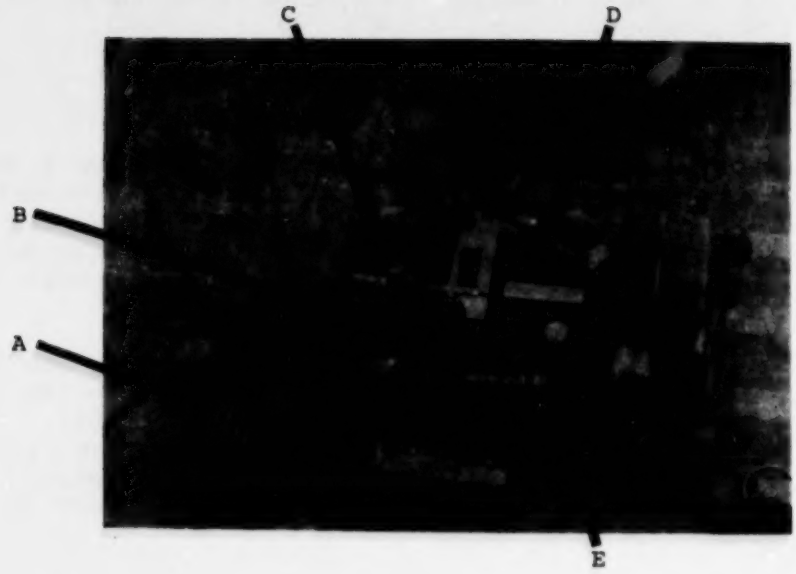
Figure 4.1 shows data from the earlier work. At low squeeze forces, approximately 1 N/mm, regenerated sorbent density ranges up to nearly 300 kg/m^3, or about 75% removal of the oil. Oil removal can be increased to 95% at high squeeze forces approaching 25 N/mm. At a squeeze force of 7 N/mm the regenerated sorbent density is approximately 130 kg/m^3. This corresponds to 90% removal of the oil from the sorbent.

Selecting a squeezing force of 7 N/mm makes the regenerator more tolerant of debris. The lower squeezing force also requires a less massive structure, resulting in a weight saving.

Friction was chosen to drive the belts because of the problems Hydronautics experienced with sorbent jamming between the chain and sprocket. The belt width was 61 cm although only 36 cm are required for the design oil recovery rate of 5.7 m^3/h. The sorbent was to be fed onto the center area of the belt, with shrouds to prevent sorbent losses off the sides of the belt.

Power was to be provided by a 2.6-kW diesel engine. Roller chain and sprockets were to transmit the power to the two drive rollers, one for each belt. (This preliminary engine is much smaller than the final design because there was no hydraulic system.)

The preliminary design called for a rotating brush scraper to remove the sorbent cubes from the lower belt, to reduce the loss of cubes to the lower collection pan.



A - hydraulic hoses
B - hydraulic oil filter
C - hydraulic oil filter pressure gauge
D - hydraulic oil reservoir
E - hydraulic oil pressure gauge

Figure 4.8. Harvesting conveyor's power supply.

Figure 4.9. Overall view of sorbent regenerator.

Development of Sorbent Regenerator--

Early in the program, it was decided to change the design to utilize hydraulic power. The switch to hydraulic power provided several advantages: the regenerator could be made lighter and more compact; flexibility in positioning the power supply relative to the regenerator was possible; a commercial power supply could be used; drive power, squeeze pressure, and belt tension force could all be provided by the same power source; squeeze force could be adjusted over a wide range and yet held nearly constant as the squeeze rollers moved up and down with varying sorbent thickness; conveyor belt speed was easily controlled over a wide range; conveyor belt jams could be cleared by powering open the squeeze rollers.

The prototype sorbent regenerator is shown in Figure 4.9. Saturated sorbent is fed into the feed hopper at the input and directly onto the lower mesh belt. Any free oil or water drains through the belt and into the primary collection trough. The motion of the lower belt transports the foam into the squeezing zone (Figure 4.10). A leveling bar at the exit from the feed hopper prevents any large debris from moving to the squeeze rollers and also acts to level off the sorbent layer.

The two regenerator belts are friction driven by a drive roller. Sprockets on the drive roller ends (Figure 4.11) are connected by an idler chain to the low speed, radial piston hydraulic motor. The hydraulic motor is located directly under the feed hopper.

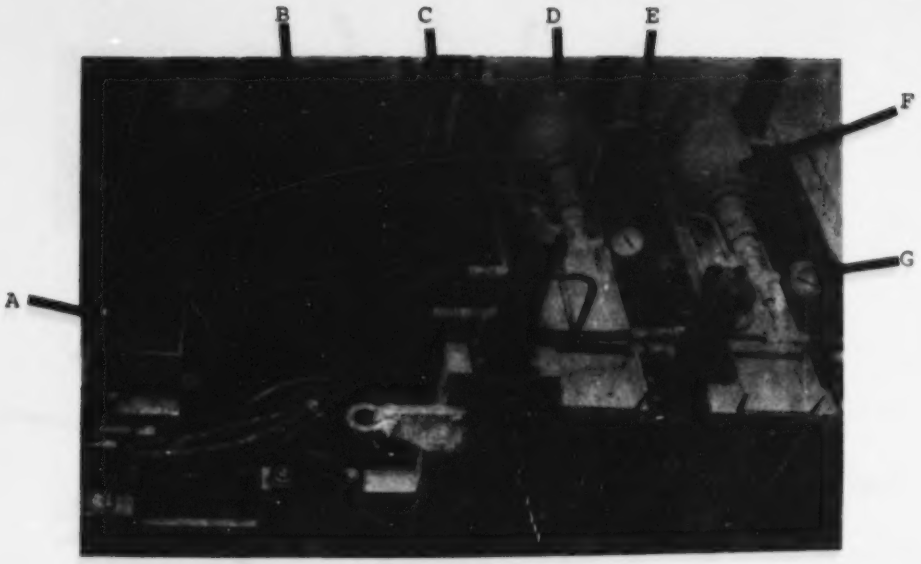
As the belts approach the squeeze zone, they converge, sandwiching the sorbent foam cubes between them. The squeeze rollers are each 254 mm in diameter. The lower two are fixed and the upper two are free to move vertically. In order to accommodate uneven sorbent flow, these rollers are connected to gimballed bearing blocks which allow the rollers to rise unevenly. Each of the four bearing blocks is connected to the rod of a double-acting hydraulic cylinder.

Three manual three-position hydraulic flow control valves are used to control the regenerator functions. One controls the conveyor drive motor, another directs the hydraulic flow to the cylinders on the upper belt tension roller to control tension. The third control valve controls the squeeze roller cylinders' force.

The hydraulic fluid pressure to the tension roller and squeeze roller cylinders is controlled by the adjustable pressure control valves located over the corresponding directional control valves. In order to keep the hydraulic pressure constant on the tension and squeeze cylinders, the "down" side of the cylinders are connected to 0.0004 m^3 hydraulic accumulators charged with nitrogen to 1400 kPa. During operation, the gas volume in the accumulators keeps the squeeze and upper belt tension force nearly constant, at the level set by the pressure control valve, regardless of squeeze and tension roller vertical movement.

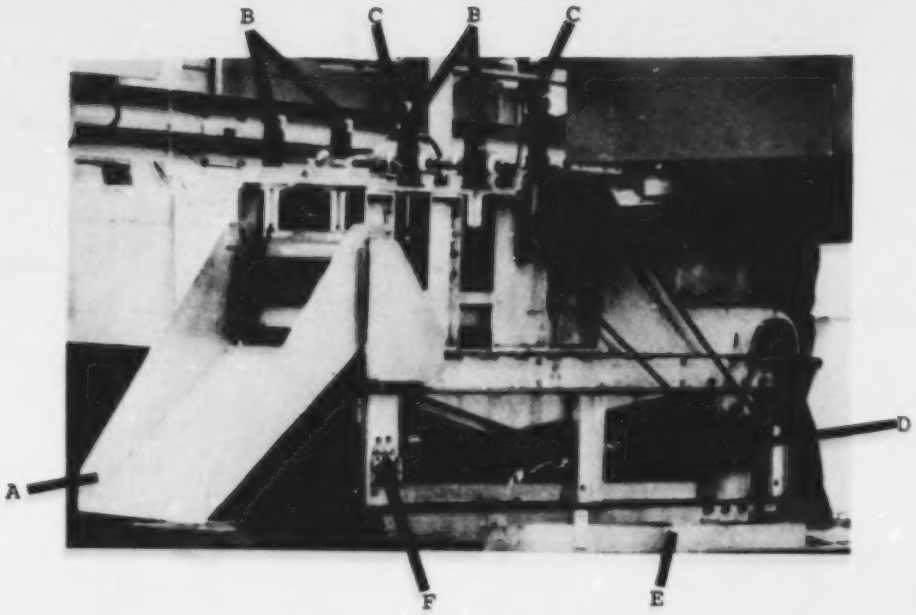
In order to keep the upper and lower conveyor belts centered on the rollers, the drive rollers are coated with elastomer and ground with a 6-mm crown in the center. Bearing blocks on the shaft of the tail roller for the lower belt have adjustment screws which are used both to tension lower belt and to prevent the conveyor belts from running to one side or the other.

Most of the oil squeezed from the sorbent drains through the lower mesh belt and drains to the bottom of the collection trough and out through the 76-mm drain fitting. To improve the flow of cold or viscous oil, the bottom wall of the collection trough is fitted with a baffled chamber filled with stainless steel wool. The collection trough can be heated by passing steam or the power supply engine exhaust gases through this heat exchange chamber. A drip pan with a separate drain fitting is located under the complete length of the regenerator unit to catch any oil dripping off the lower belt or other parts of the unit.



A - lower belt
B - upper belt
C - upper belt tension roller
D - tension accumulator
E - tension accumulator pressure gauge
F - squeeze accumulator
G - squeeze accumulator pressure gauge

Figure 4.10. Detail of sorbent regenerator.



A - discharge chute
B - squeeze hydraulic cylinder
C - upper belt tension hydraulic cylinder
D - chain-and-sprocket drive
E - chain guard (removed)
F - bearing adjustment screw

Figure 4.11. Sorbent regenerator with chain guard removed.

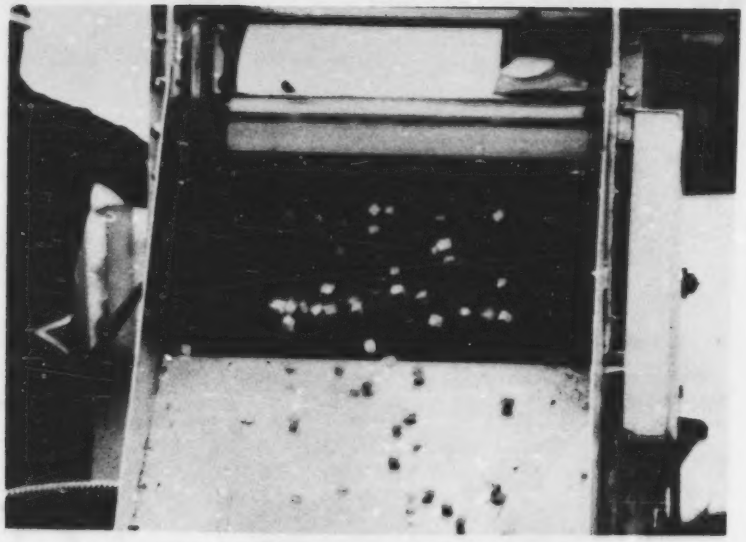
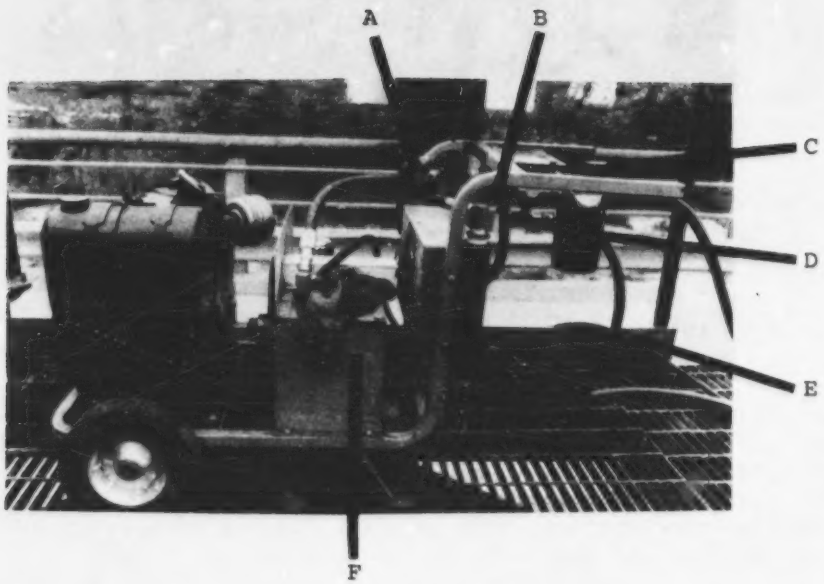


Figure 4.12. Sorbent cubes tumbling down regenerator's discharge chute.

Counterrotating cylindrical bristle brushes sweep the sorbent cubes off the upper and lower belts at the discharge end of the regenerator, causing the sorbent to fall by gravity down the removable aluminum discharge chute (Figure 4.12). At the bottom of the chute, the sorbent can be fed onto a conveyor or into tote pans or a collection hopper.

The regenerator unit weighs approximately 820 kg. It can be lifted either by a fork lift from the discharge end or by means of a wire rope bridle attached to the two eyebolts on the frame and the shackle on the end of the feed hopper. When used in the field, the regenerator can be operated in the bed of a pickup truck.

Power for the regenerator is provided by a commercially available, gasoline engine-driven 12-kW hydraulic power supply mounted on a rubber-wheeled portable frame (Figure 4.13). The unit has an output capacity of 2 m^3/h at 14,000 kPa. The power supply engine is equipped with a manual start for maximum reliability. A flow-control valve is provided to unload the hydraulic pump during starting and to provide a remote means for stopping the regenerator if necessary. Three hoses connect the power supply to the regenerator unit by means of quick-connect fittings. Two 13-mm hoses are the main hydraulic supply and return, while the smaller hose is the case drain return from the regenerator drive motor.



A - throttle
B - control valve
C - hydraulic oil filter pressure gauge
D - hydraulic oil filter
E - hydraulic hoses
F - hydraulic oil reservoir

Figure 4.13. Sorbent regenerator's power supply.

The reasoning behind replacing the diesel engine and diesel drive with a hydraulic power supply driven by a gasoline engine was the same as for the harvesting conveyor. The benefits were a weight saving, increased operational flexibility, and greater availability of parts. The operational flexibility in positioning the power supply compensates for whatever loss of safety may accompany the replacement of a diesel engine with a gasoline engine.

Post-Test Modifications to the Sorbent Regenerator--

The major desirable modification to the sorbent regenerator that became evident during the tests at OHMSETT was to provide more positive drive and tracking for the belts. Several other minor items were also modified.

Throughout most of the tests at OHMSETT, the only problem with the belts was that they needed occasional adjustment to track properly. Approximately every 30 minutes a technician would make the small adjustment. In later tests with an oil of high lubricity, one of the belts would occasionally stop because the drive roller lost friction, and subsequently the other belt would stop. The addition of a slide bed with centering strips and tracking guides solved the tracking problems for the lower belt, even if the regenerator is not level.

As tested at OHMSETT, several small rollers supported the lower, stainless steel belt between the drive roller and the first squeeze roller. Crowned rollers provided tracking, but it was apparent that more positive tracking was needed. When the regenerator was not level, the belt would track to one side.

This problem was solved by installing a slide bed to replace the small support rollers. Nylon strips, riveted to a 1.4-m long aluminum plate in a chevron pattern, center the belt when the regenerator is nearly level. Crowned rollers augment this tracking. When the regenerator is not level, guides along the sides of the belt prevent it from walking too far to one side or the other. The guides are made of seasoned oil-soaked oak.

Although no modifications were made to the unit, prior to its delivery, to eliminate the belt slipping encountered with high lubricity oil, it is felt that applying conventional lagging to the upper belt drive roller in a chevron pattern will both improve the driving reliability and the belt tracking.

Other modifications to the sorbent regenerator include adding a splash guard, and plumbing two discharge lines into one line (Figure 4.14).

As tested, the regenerator used two hoses to remove the oil, one connected to the primary oil collection sump and the other to the drip pan. To simplify this, both the upper and the lower collection pans were brought to a common discharge connection through a 2-way, 3-port valve. In the normal valve position, the pump takes suction from the main upper collection pan. When the lower pan begins to fill, which only happens occasionally, the operator momentarily changes the valve position and the pump takes suction from the lower pan. A male quick-connect fitting, compatible with the 76-mm discharge hose, attaches to the elbow. The regenerator's hydraulic motor can be seen opposite the 3-way valve in Figure 4.14.

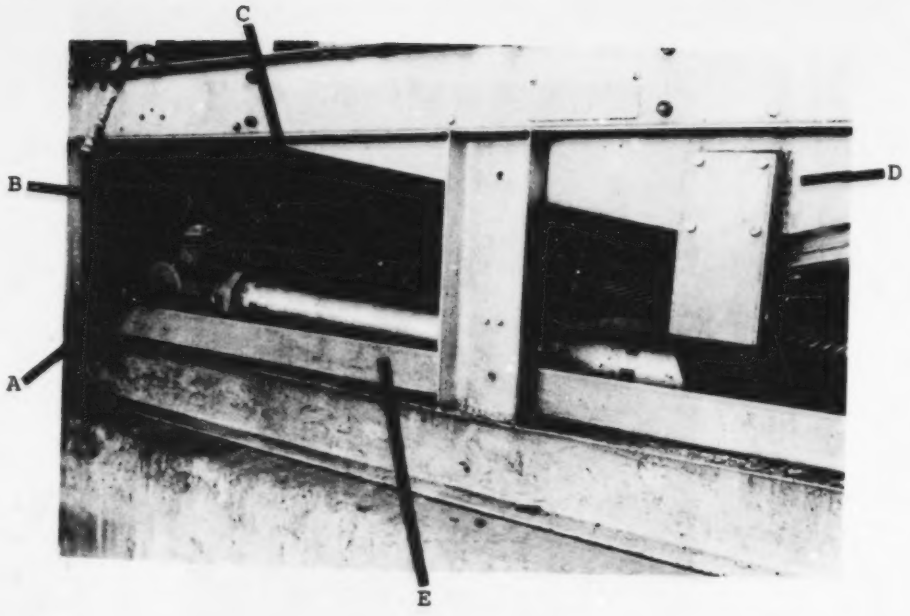
Final Design of the Sorbent Regenerator--

The regenerator squeezes oil from the sorbent cubes by means of converging belts. The lower belt, made of stainless steel wire cloth, is porous, allowing the oil to drain through. The upper belt has polyurethane covers which make it highly abrasion-resistant and impervious to oil. Three rollers move vertically by means of hydraulic cylinders: one roller tensions the upper belt, while the other two provide the squeeze force. Characteristics of this unit are contained in Table 4.3.

With a mass of 820 kg, the sorbent regenerator is the only component of the system that two people cannot maneuver. However, its size allows it to be carried and operated in the back of a pickup truck (Figure 4.15). The unit's dimensions are 2.44 m long by 0.94 m wide by 1.77 m high overall.

The power supply can also be seen in Figure 4.15. The hydraulic pump driven by a 12-kW gasoline engine delivers 2 m^3/h of hydraulic fluid at a pressure of 14,000 kPa. The hydraulic system is fully described later in this section.

Post-test modifications to the sorbent regenerator include improved drive and tracking for the belts, piping and a valve to consolidate the discharge lines into one, and a splash guard.



A - 3-port, 2-way valve
B - discharge port
C - hydraulic motor
D - upper collection pan
E - lower collection pan

Figure 4.14. Post-test modifications to the regenerator: plumbing to combine the two discharge ports.

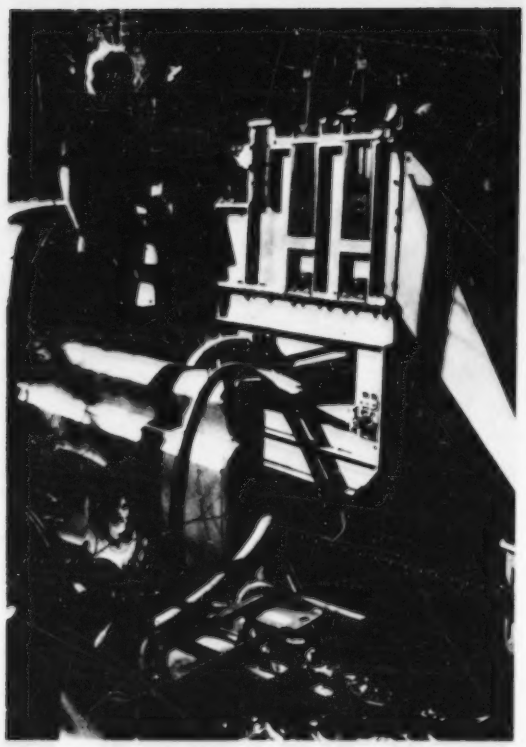


Figure 4.15. Sorbent regenerator operating in the back of a pickup.

TABLE 4.3. CHARACTERISTICS OF THE SORBENT REGENERATOR

Length	2.44 m overall
Width	0.94 m
Height	1.77 m overall
Mass	820 kg
Upper belt type and size	Polyester conveyor belting with polyurethane coating, 610 mm wide, 2.7 m long
Upper belt drive	Friction
Lower belt type and size	Balanced weave, stainless steel wire cloth, 610 mm wide, 6.1 m long, 7.1 mm thick
Lower belt drive	Friction; tracking provided by herringbone slide bed, and tracking guides
Belt speed	To .61 m/s
Squeeze force	Adjustable, nominally 7 N/mm
Number of squeezings	2
Power unit	Hydraulic pump (2 m^3/h at 14,000 kPa) driven by a 12-kW gasoline engine

SECTION 5

SYSTEM TESTING AT OHMSETT

Extensive tests were conducted at U. S. Environmental Protection Agency's OHMSETT test facility. The results showed that the sorbent oil recovery system is an effective means of recovering accidental spills, particularly in choppy waters that defeat many other types of cleanup devices. The results also indicated several desirable modifications to the system.

TEST PROGRAM

Test Layout

The test layout simulated field conditions and allowed a realistic evaluation of the performance envelope of the system. Factors involved in selecting the test layout were:

1. There had to be adequate contact time between the sorbent and the oil. This dictated the distance between the broadcast and recovery units as a function of speed.

2. The broadcast and recovery of the sorbent had to be carried out in a test area in which side losses of both oil and sorbent were controlled. This dictated the maximum funneling angle at a given test speed.

3. The area of sorbent coverage had to be large enough to minimize "over-spray" losses of the sorbent past the funneling boom, but small enough to be manageable. This dictated the boom "mouth" opening.

4. Provision had to be made for transfer of personnel and recovered sorbent after the completion of a test.

5. The test layout had to be compatible with existing EPA tank procedures and equipment inasmuch as possible.

In line with the above factors, a preliminary test layout was made as shown in Figure 5.1. With the planned test layout the following contact times were calculated:

Velocity		Contact Time
Knots	m/s	s
1	.5	36
2	1.0	18
4	2.1	9
6	3.1	6

A 15-second or greater contact time between sorbent and oil was considered desirable from earlier work with absorption, and this could be obtained at the 1- and 2-knot speeds. Reasonable contact times could also be obtained at the higher speeds.

A funneling angle of 0.18 rad is obtained with the planned test layout. This gives a velocity normal to the boom of 0.7 knots at a 4-knot tow speed and 1.1 knots at a 6-knot tow speed. This was adequate to prevent significant oil or sorbent losses while funneling.

The 4.9-m boom spacing allowed adequate room for broadcasting the sorbent. It also allowed in excess of 5.7 m^3/h oil encounter rate for a 0.75-mm slick at a 1-knot tow speed.

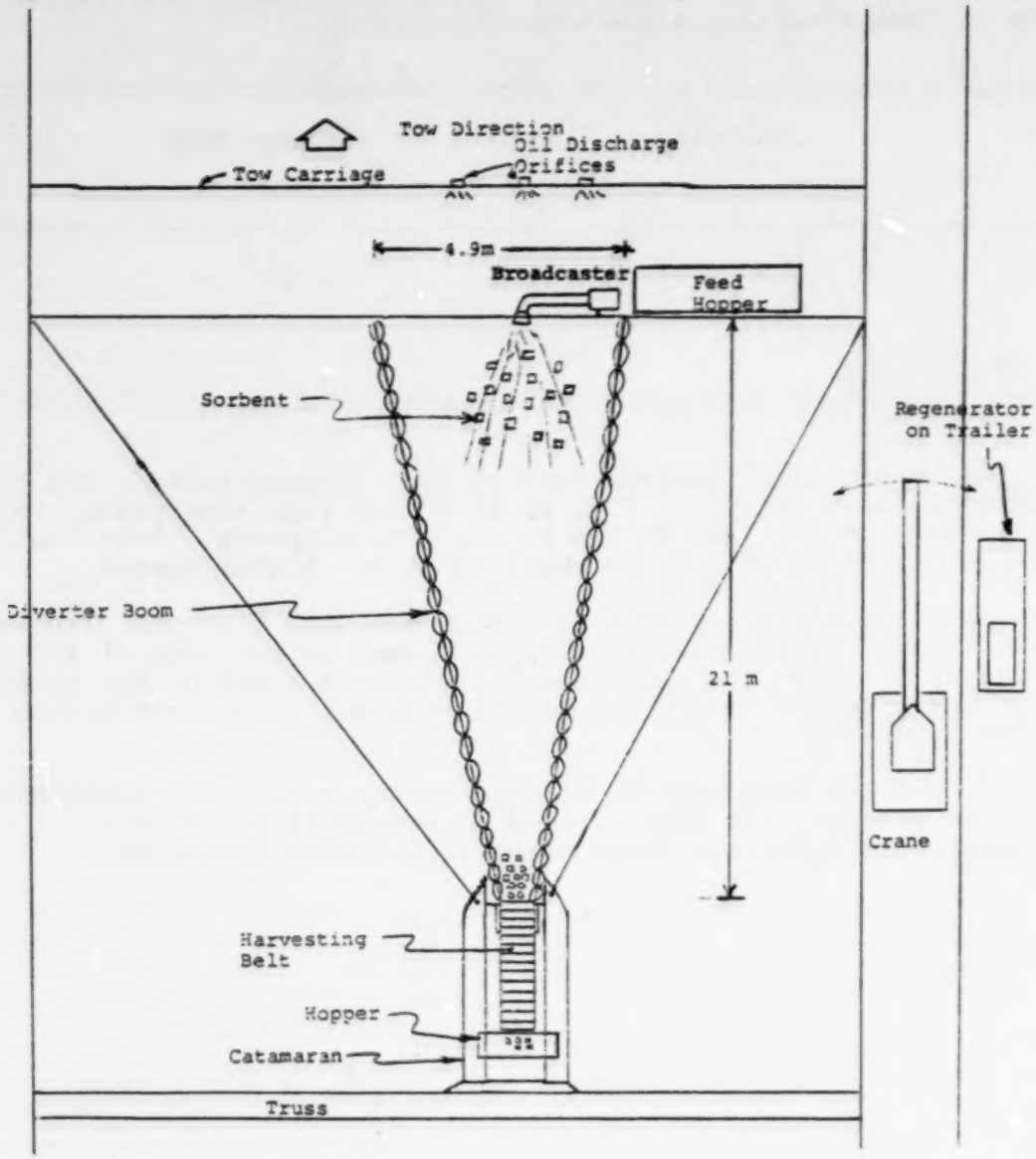


Figure 5.1. OHMSETT test tank arrangement.

Test variables

Tests were run over a range of sweep speeds, oil thicknesses, wave heights, and oil types. The independent variables (parameters to be varied) and dependent variables (variables to be measured) were:

Independent Variables	Dependent variables
1. Sweep speed (1,2,4,6 knots)	1. Recovery rate
2. Oil thickness (0.75, 1.5 mm)	2. Oil fraction (ratio of collected oil to total collected liquid volume)
3. Waves (calm to 0.6 m wave height)	3. Volumetric efficiency (volume of oil recovered per unit volume of sorbent recovered)
4. Wind speed (variable, depending on weather during test)	4. Throughput efficiency (percentage oil encountered which was recovered)
5. Oil type (light, heavy)	5. Sorbent losses
6. Sorbent broadcast rate	

The independent variables were controlled or measured as follows:

1. Sweep speed

The sweep speed was determined by the rate at which the tow carriage was pulled down the length of the tank. Sweep speed was set for each run in accordance with the predetermined test matrix and held constant for the entire run.

2. Oil thickness

The test matrix specified an average slick thickness for each test run. Using the test run advance speed and the fixed width at the mouth of the diverter booms, the required flow rate to obtain the desired slick thickness was calculated. The oil distribution pump and control valves were

then adjusted to this flow rate prior to each test run. During the run, the oil was sprayed onto the water from the distribution manifold nozzles on the leading edge of the tow carriage. The actual slick thickness was calculated after each test from the total oil volume distributed, sweep speed and boom width. For the purpose of this calculation, it was assumed that the slick was uniform in thickness.

3. Wave conditions

The wave type desired for each run to match the predetermined test matrix was generated using the OHMSETT tank wave maker. Using previously calibrated settings for the wave flap stroke, speed and phase, the type of wave (regular or chop), wave height and period were adjusted. The wave maker was not operated during calm water test runs.

4. Wind speed

No control could be exercised over wind speed or direction. The wind speed and direction was measured and recorded for each test run.

5. Oil type

The type oil laid down on the water was in accordance with the predetermined test matrix. It was controlled by connecting the appropriate oil storage container to the oil distribution system.

6. Sorbent broadcast rate

The sorbent broadcast rate was the most difficult independent variable to control. Although the test matrix was designed around discrete sorbent broadcast rates, it was not possible in practice to accurately preselect the sorbent rate. Instead, the total sorbent volume broadcast during a test run was determined by calculation after each run, from the weight of saturated sorbent collected and the average density of the saturated sorbent. The sorbent broadcast rate was then obtained by dividing the total sorbent collected by the broadcast time.

It had been planned to control the sorbent broadcast rate by controlling the speed of the screw conveyor which carried the sorbent from the feed hopper to the broadcaster. However, good speed control was not obtainable and the sorbent transport rate was not constant at a fixed screw speed, because of sorbent bunching and surging in the conveyor.

Measurement of the dependent variables were made as follows:

1. Recovery rate

The total operating time of the recovery device during a test was measured. The sorbent was weighed before and after the tests, and the recovered oil and water was measured by difference. This weight was converted to a volume and the recovery rate was calculated as collected volume divided by operating time. Also, when the sorbent was regenerated, the collected volume of oil and water was measured, and a second determination of the recovery rate was made using this information.

2. Oil fraction

The liquid from the regenerator was collected, and the oil content was measured by determining the oil-water interface. The oil fraction was calculated by dividing the volume of collected oil by the total volume of liquid recovered.

3. Volumetric efficiency

The volumetric efficiency is the ratio of the oil collected to the volume of sorbent recovered. The oil recovered was determined by direct measurement. The recovered sorbent volume was determined by sampling the recovered saturated sorbent and measuring its density and dividing the weight of the recovered sorbent by this density.

4. Throughput efficiency

Throughput efficiency was defined as the percentage of the oil encountered which was recovered. It was calculated by dividing the recovered oil volume by the volume of oil deployed.

5. Sorbent losses

Sorbent lost past the system was swept back after a test run with the sweep boom on the tow bridge. The number of sorbent cubes were estimated and compared to the volume broadcast during the test run. Losses were negligible on all runs.

Test Procedure

Before the actual testing began, all equipment was assembled and checked out. Several dry runs were made to check out test procedures.

The general test procedure for these tests was as follows:

A. Before test

1. Set tow speed
2. Set up sorbent broadcast and recovery hoppers
3. Turn on broadcast and recovery equipment
4. Set oil flow rate
5. Set wave height and period and begin wave generation
6. Set sorbent screw conveyor speed to desired broadcast rate
7. Set up still and motion picture photographic equipment
8. Measure water temperature, air temperature, wind speed, and record general weather conditions
9. Start broadcaster and harvester

B. During test

1. Tow apparatus down tank
2. Release oil at controlled rate
3. Broadcast sorbent
4. Recover sorbent and catch in hoppers
5. Sample recovered sorbent
6. Photograph test

C. After test

1. Weigh recovered sorbent
2. Estimate volume of lost sorbent
3. Regenerate collected sorbent
4. Measure volume of collected oil
5. Measure water content of collected oil
6. Measure density of both the saturated and the regenerated sorbent.

A total of 33 individual test runs were conducted. On seven of these runs the run was aborted because of jamming of the broadcaster and no meaningful data were collected. This jamming resulted from choking the broadcaster by supplying sorbent to it at a faster rate than it could handle. The jamming was just one manifestation of the more general problem of inability to closely control the sorbent broadcast rate.

The test plan matrix was based on having the sorbent broadcast rate as a controllable independent variable. It was assumed that this could be done by using a screw conveyor with a variable speed drive to supply the sorbent to the broadcaster. In preliminary tests with dry, lightweight sorbent, a linear relationship was found between the sorbent delivery rate from the conveyor and the screw speed. However, when heavier, pre-wetted sorbent was used, the conveyor delivery rate ceased to be constant or linearly proportional to the screw speed. The sorbent in the feed hopper and screw conveyor no longer behaved like a fluid, instead it compressed and bunched causing surging and uneven delivery from the conveyor. As a result, the sorbent broadcast rate was not a well controlled variable. The average rate for each run had to be determined at the conclusion of the run from the recovered sorbent density and total weight measurements.

The inability to accurately control the sorbent broadcast rate precluded the following of the test matrix which specified the broadcast rate to be used for each run. It also prevented the duplication of test runs to check their repeatability.

The test conditions and the results for all test runs are contained in Table 5.1.

TEST RESULTS

General Conclusions

Because of the relatively limited number of test runs, the lack of repeatability and the number of variables associated with the system, the test results have more qualitative meaning than quantitative. There were many sources of inaccuracy in the measured data. Slick thickness and sorbent distribution were not uniform across the slick surface, broadcast rates were not steady, collected sorbent and regenerated sorbent densities were determined by samples which may not have been truly representative. The fact that on two tests throughput efficiencies in excess of 100% were obtained, indicates the danger of putting too much reliance on the actual numerical results. The throughput efficiency of 117% for run 16 resulted from the volume of oil recovered being measured as 0.01 m^3 greater than the amount applied. A 0.01 m^3 error could easily have resulted from residual oil in the regenerator and drain hoses, or from an error of a few millimeters in measuring the thickness of the oil in the collection tank.

Several general conclusions or trends can be derived from the test results.

TABLE 5.1. TEST CONDITIONS AND RESULTS

Test #	Run Speed (m/s)	Slick Thickness (mm)	Viscosity (mm^2/s)	Sorbent Rate (m^3/s)	Wave (2) Height (m^3/s)	Recovery Rate (m^3/h)	Throughput Efficiency (%)	Oil Fraction	Vol. Liq.Rcvd / Vol.Sorb.Rcvd (m^3/m^3)	Volumetric Efficiency (%)
1	0.76	0.54	6.3	0.0032	calm	6.3	84	0.62	0.79	48
2	0.51	0.81	6.3	0.0050	0.3-m R	8.1	108 (3)	0.48	0.79	38
3	1.02	0.54	6.3	0.0054	calm	9.6	82	0.57	0.74	42
4 (1)	1.27	0.50	6.3							
5	0.76	0.54	6.3	0.0024		5.4	71	0.66	0.80	53
6	0.76	0.54	6.3	0.0021		5.5	62	0.74	0.82	60
7	0.76	0.54	6.3	0.0057		7.3	86	0.44	0.63	28
8	1.02	0.54	6.3	0.0031		8.5	78	0.68	0.93	63
9 (1)	1.02	0.56	6.3							
10	1.27	0.50	6.3	0.0048		10.5	90	0.63	0.78	50
11	1.27	0.51	6.3	0.0031		6.0	50	0.70	0.66	46
12	1.02	0.79	6.3	0.0031		8.5	52	0.79	0.80	63
13	1.02	0.24	6.3	0.0024		4.6	88	0.62	0.70	44
14	1.02	0.84	6.3	0.0035	0.3-m R	7.9	46	0.73	0.81	59
15	1.02	0.55	6.3	0.0029		7.9	70	0.78	0.81	63
16	1.02	0.21	6.3	0.0032		4.8	117 (3)	0.56	0.60	34
17	1.02	0.29	6.3	0.0031	0.3-m W	5.5	96	0.55	0.73	40
18	1.02	0.54	6.3	0.0038		9.1	79	0.70	0.79	55
19	1.02	0.80	6.3	0.0036		9.2	60	0.75	0.78	58
20	1.52	0.41	6.3	0.0042		9.2	72	0.67	0.74	50
21	2.54	0.28	6.3	0.0074		6.8	48	0.38	0.55	20
22	2.03	0.30	6.3	0.0043	calm	5.4	42	0.51	0.49	25
23	2.54	0.22	6.3	0.0057		5.2	43	0.38	0.49	19
24	1.02	0.53	295	0.0052		8.5	81	0.76	0.51	38
25 (1)	1.02	0.55	295							
26	1.02	0.54	295	0.0051		7.8	76	0.60	0.65	39
27	1.02	0.28	295	0.0052		4.4	84	0.63	0.45	29
28 (1)	0.51	0.69	295							
29 (1)	0.51	0.78	295							
30 (1)	0.51	0.65	295							
31 (1)	0.51	0.40	295							
32	2.03	0.32	295	0.0052		7.0	57	0.74	0.39	29
33	1.52	0.40	295	0.0056	0.3-m W	8.7	80	0.75	0.49	36

(1) Broadcaster jammed - Test aborted
(2) R = Random Harbor Chop
W = Regular Wave, 1.5-s Period
(3) Experimental error, these values should not exceed 100%.

Throughput efficiency tends to be inversely proportional to run speed. The most likely cause for this is that residence time of the sorbent in the slick was reduced as speed increased. This is because the distance involved remained fixed throughout the tests. These distances were from the broadcaster to the harvester, and the length of the harvesting conveyor. As a result, the time the cubes spent absorbing oil and draining decreased with increasing speed. This trend occurred for both light and viscous oils. As evidence, compare the results of tests 13 v. 23 (light oil, calm water), 17 v. 21 (light oil, regular waves), and 27 v. 32 (viscous oil, calm water):

Test No.	Speed (m/s)	Throughput Efficiency (%)
13	1.02	88
23	2.54	43
17	1.02	96
21	2.54	48
27	1.02	84
32	2.03	57

These pairs of tests were run with nominally the same slick thicknesses. (See Table 5.1 for complete test data.)

With the light oil, throughput efficiency tended to be the same or higher in waves than in calm water, probably due to greater mixing. On the other hand, throughput efficiency with the viscous oil does not appear to be affected by waves. Comparison of test 13 with tests 16 and 17 (run speed 1.02 m/s), and test 21 with test 23 (run speed 2.54 m/s) show this weak trend.

Test No.	Wave Condition	Throughput Efficiency (%)
13	calm	88
16	0.3-m regular wave	117*
17	0.3-m random wave	96
23	calm	43
21	0.3-m regular wave	48

* experimental error, this value should not be greater than 100%

Volumetric efficiency (volume of oil recovered per unit volume of sorbent recovered) increased with increasing slick thickness. This was true for both light and viscous oils and was probably due to the fact that with thinner slicks, more sorbent cubes competed for the same amount of oil. Tests 17, 18, and 19 were all with the light oil at a run speed of 1.02 m/s with nearly constant broadcast rate, and were all conducted in 0.3-m regular waves. Tests 27 and 26 were viscous-oil tests in calm water at the same speed, also with nearly the same sorbent rate.

Test No.	Slick Thickness* (mm)	Volumetric Efficiency (%)
17	.29	40
18	.54	55
19	.80	58
27	.28	29
26	.54	39

* calculated from oil distribution rate and width of sweep

Throughput efficiency is proportional to sorbent broadcast rate, while volumetric efficiency is inversely proportional to sorbent broadcast rate at low speed. With less sorbent in the slick (low rate), each cube absorbs a larger amount of oil, which increases volumetric efficiency. On the other hand, throughput efficiency suffers at lower sorbent rates because there is not enough sorbent in the slick. Test run 1, 5, 6, and 7 illustrate these points. These tests were conducted at the same tow speed, with the same slick thickness, and with light oil in calm water. Only the sorbent broadcast rate varied.

Test No.	Run speed (m/s)	Sorbent broadcast rate (m^3/s)	Volumetric efficiency (%)	Throughput efficiency (%)
7	0.78	.0057	28	86
1	0.78	.0032	48	84
5	0.78	.0024	53	71
6	0.78	.0021	60	62

At higher speeds, this same trend for throughput efficiency holds, but volumetric efficiency appears to be independent of sorbent broadcast rate. Compare the results of tests 10 v. 11 and 32 v. 22. Each pair of tests was conducted in calm water with very nearly the same amount of oil; only the sorbent broadcast rate varied.

Test No.	Run speed (m/s)	Sorbent broadcast rate (m^3/s)	Volumetric efficiency (%)	Throughput efficiency (%)
10	1.27	.0048	50	90
11	1.27	.0031	46	50
32	2.03	.0052	29	57
22	2.03	.0043	25	42

Volumetric efficiency for the light oil tended to be higher with a longer residence time (as evidenced by slower speed), but was unaffected by residence time for the viscous oil. Tests 8 and 11 were conducted with the light oil, and with the same nominal slick thickness and sorbent broadcast rate.

Test No.	Run speed (m/s)	Volumetric efficiency (%)
8	1.02	63
11	1.27	46

On the other hand, compare the results for the viscous oil. The only significant difference in parameters between tests 27 and 32 was residence time.

Test No.	Run speed (m/s)	Volumetric efficiency (%)
27	1.02	29
32	2.03	29

These results appear anomalous. It was witnessed during the OHMSETT tests that the cubes absorbed the light oil far faster than the viscous oil; therefore, it would seem that the above trends should be the other way around.

The last general conclusion is that winds up to 15 knots have negligible effect on system performance. This was the most severe environmental condition during the tests at OHMSETT, and the wind did not blow any sorbent cubes away. Of more significance were waves breaking over the boom; but even at 2.57 m/s in breaking waves, sorbent cube losses were only 2%.

Data Correlation

In an attempt to evaluate the performance of the system with the wide range of variables considered, the data was entered into a computerized nonlinear multivariable regression analysis. The program can handle linear combinations of nonlinear functions of the forms:

$y = k \cdot x + b$ $\qquad$ $y = k \cdot \log(x) + b$

$y = k \cdot x^{\frac{1}{2}} + b$ $\qquad$ $y = k \cdot e^{x} + b$

$y = k \cdot x^{2} + b$ $\qquad$ $\log(y) = k \cdot \log(x) + b$

In summary, system performance is a trade-off between throughput efficiency, which requires high sorbent rates, and the oil fraction in the recovered liquid, which required low sorbent rates. Sorbent rates in the range of 0.004 to 0.006 m^3/s appear to be best for the ranges of flow velocity, slick thickness, and viscosity that were used in the OHMSETT tests.

Discussion of the nonlinear regressions follows.

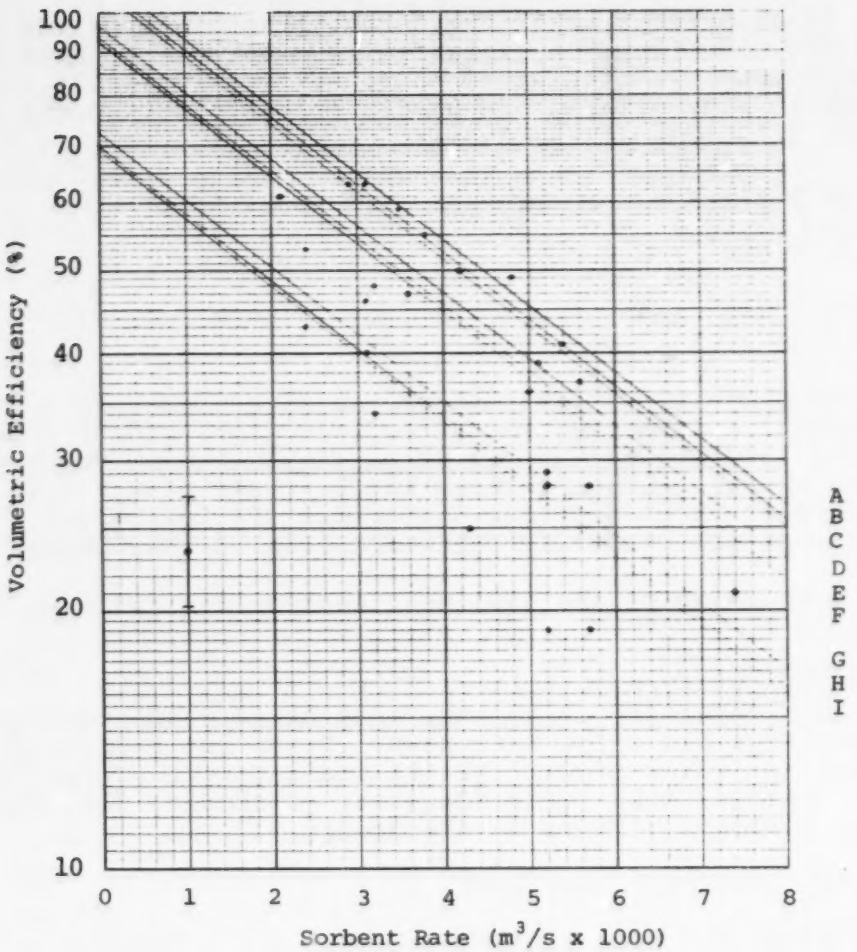
Volumetric efficiency (Figure 5.2)--

The volumetric efficiency is a significant function of sorbent rate and slick thickness. It is not significantly affected by water flow velocity, indicating that residence times in these tests were adequate. Viscosity does not significantly affect volumetric efficiency.

The nonlinear regression is:

$$\log VE = 0.0523 - 0.0789R + 0.0263\sqrt{V} + 0.385 \log T$$
$$r = 0.8659$$

where VE = volumetric efficiency
R = sorbent broadcast rate (m^3/s)
V = velocity (m/s)
T = slick thickness (mm)



	Slick Thickness (mm)	Flow Velocity
A	0.80	2.54
B	0.80	1.02
C	0.80	0.51
D	0.54	2.54
E	0.54	1.02
F	0.54	0.51
G	0.25	2.54
H	0.25	1.02
I	0.25	0.51

Figure 5.2. Nonlinear regression of volumetric efficiency.

Oil Fraction in Recovered Fluid (Figure 5.3)--

The fraction of oil in the oil-water mixture varies as a function of all of the independent variables. Most significantly, low sorbent rates and high viscosity improve the proportion of oil in the recovery stream. Of secondary importance, but still significant, are the effects of flow velocity (higher velocity improves performance) and slick thickness (higher proportion of oil with increasing thickness). Higher flow velocity increases the oil fraction in the recovered liquid, in general, because the contact time is less. The sorbent cubes land on the oil and absorb it first. With shorter contact times, there is less time to absorb water. A thicker slick also results in a higher oil fraction for the same reasons. Only with the high viscosity lubricating oil at low sorbent rates did the fraction of oil in the recovered fluid exceed 90%.

The nonlinear regression of oil fraction is:

$$F = 0.0101 - 0.0641R + 0.621V + 0.221 \log T + 0.0064 \sqrt{U}$$
$$r = 0.7445$$

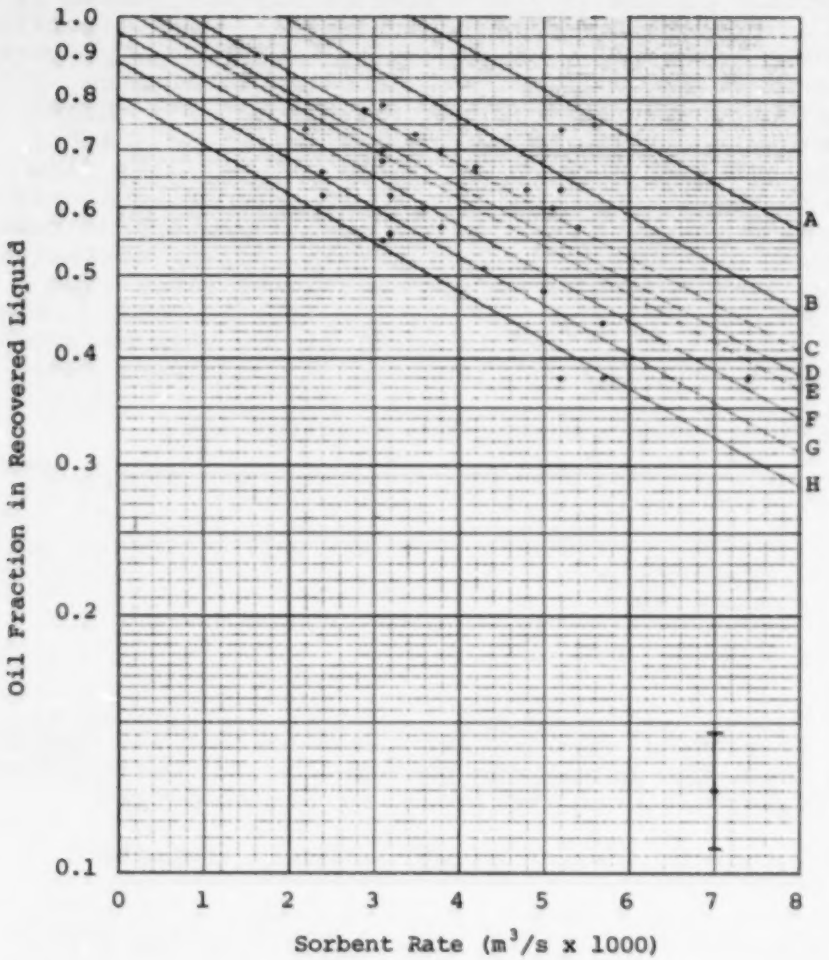
where F = oil fraction
U = viscosity (mm^2/s)

Throughput Efficiency (Figure 5.4)

Throughput efficiency is significantly affected by all variables. In general, the thinner the slick and the higher the sorbent rate, the better the performance. Increasing water flow rate severely reduces the amount of oil recovered.

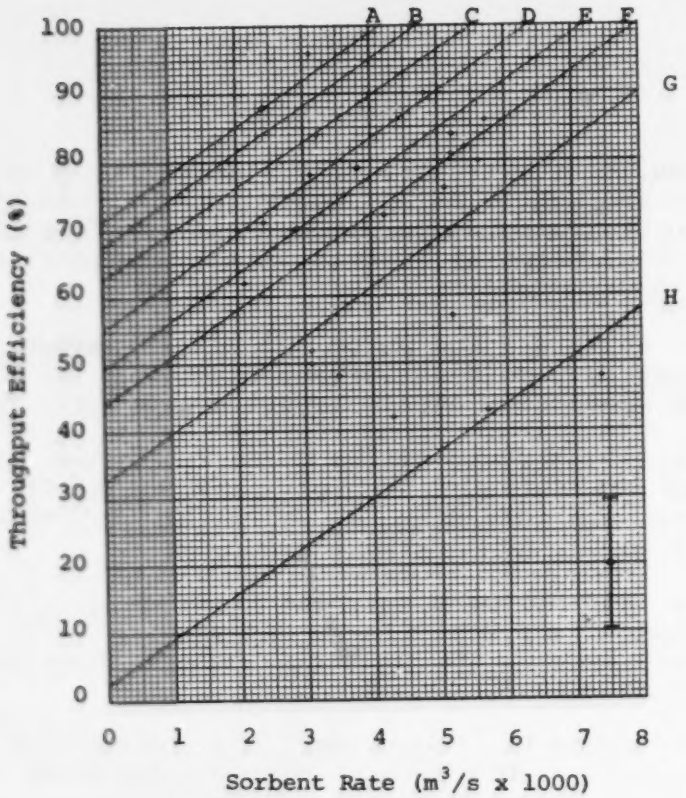
The nonlinear regression of oil recovery throughput efficiency is:

$$E = 128.8 + 7.023R - 42.8V - 61.63T - 3.23 \log U$$
$$r = 0.854$$



	Flow Velocity (m/s)	Slick Thickness (mm)	Viscosity (mm^2/c)
A	2.54	0.54	295
B	1.02	0.54	295
C	1.02	0.80	6.3
D	2.54	0.25	6.3
E	1.02	0.54	6.3
F	0.51	0.54	6.3
G	1.02	0.25	6.3
H	0.51	0.25	6.3

Figure 5.3. Nonlinear regression of oil fraction in recovered liquid.



	Flow Velocity (m/s)	Slick Thickness (mm)	Viscosity (mm^2/s)
A	0.51	0.54	6.3
B	1.02	0.25	6.3
C	1.02	0.25	295
D	0.51	0.80	6.3
E	1.02	0.54	6.3
F	1.02	0.54	295
G	1.02	0.80	6.3
H	2.54	0.25	6.3

Figure 5.4. Nonlinear regression of throughput efficiency.

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APPENDIX

DESIGN RATIONALE FOR THE PNEUMATIC OIL-SORBENT TRANSPORT/BROADCASTING SYSTEM

by William T. Lindemuth

HYDRONAUTICS, Incorporated was subcontracted to provide technical support to Seaward International, Inc., in the performance of its contract No. 68-03-2138 with the Environmental Protection Agency. HYDRONAUTICS' primary responsibility was for the design, prove-out and documentation of the pneumatic oil-sorbent transport/broadcasting subsystem.

PRELIMINARY DESIGN

The preliminary design of the pneumatic broadcasting system was predicated on the design method developed by HYDRONAUTICS, Incorporated under contract to EPA and described in Reference 1. An important consideration in the design of this subsystem was the requirement that it be self-contained, capable of being carried by two men (i.e., less than 91 Kg). This constraint led directly to the selection of the largest available blower compatible with the weight limitation and a gasoline engine to drive the blower.

The blower selected was a Dayton "High Pressure Blower" No. 4C131 which has an open material handling (OMH) wheel (as recommended in Reference 1) of 34 cm (13½") diameter. The inlet diameter is 20 cm (8") and the outlet is 18 x 15 cm (7-1/8" x 5-3/4"). The blower is mounted on its side with the inlet facing upward to allow gravity feed of the sorbent cubes. A cone-shaped hopper is affixed over the inlet, both to increase the effective feed area and to minimize inlet losses to the blower. An adapter is added to the outlet to join with 20 cm (8") diameter transport ducting.

The galvanized transport duct is nominally 7.3 m (24 feet) long including a 1.8 m section of flexible duct which allows the sheet metal nozzle to be aimed manually to direct the sorbent broadcasting as desired. The nozzle is incorporated to direct the sorbent downward and to widen the broadcast pattern.

The design point for sorbent transport was based on a sorbent density of 9.13 g/cc and recommendations of Reference 1, namely: duct velocity = 13.7 m/sec, and sorbent weight/air weight, $W_c/W_a = 1$. The preliminary calculations for the blower power follow.

Duct Area = $\pi/4 \times 20^2 = 314$ cm^2

Air Volume, $\dot{V}_a = \frac{314 \times 13.7}{10^4} = 0.43$ m^3/sec (910 cfm)

Air Density = 1.2×10^{-3} g/cc (.075 lb/ft^3)

Air Weight, $W_a = 1.2 \times .43 = .52$ Kg/sec

Sorbent Volume at 0.13 g/cc =

$\dot{V}_c = \frac{1.2 \times 10^{-3}}{0.13} \times 0.43 = 4 \times 10^{-3}$ m^3/sec (8.5 cfm)

Head Loss in Duct (Reference 1, p. 131)

Note: English units hereafter.

$$h = \frac{V^2}{0.445 \times 10^4} \cdot \left(f \cdot L/D + 0.5 + \frac{W_c}{W_a} + \frac{C\, W_c L}{W_a 69.4} \right)$$

f = air friction factor = 0.013

0.5 = nozzle loss coefficient (estimate for fixed nozzle)

C = sorbent friction factor = 1.5 (estimate)

$$h = \frac{0.45^2}{.445}\,(0.013 \cdot 36 + 0.5 + 1.0) + \frac{1.5 \cdot 24}{69.4}$$

$$= 1.4 \text{ in. } H_2O$$

F_h = 0.3 (Ref. 1, p. 139) (conservative for sorbent cubes)

Apparent Head = h/F_h = 4.65 in. H_2O

$$\dot{V}_a / \sqrt{h} = 910/\sqrt{4.65} = 422$$

Read off blower characteristic curve (Figure A-1):

$$\dot{V}_a/N = 0.365$$

$$\therefore N = 910/0.365 = 2500 \text{ RPM}$$

$$\underline{\text{Air Horsepower}} = \dot{V}_a \times H/(\eta \times 6350)$$

$$\sim \frac{910 \times 4.65}{0.7 \times 6350} = 1.0 \text{ hp}$$

$$\text{"}\underline{\text{Chip power}}\text{"} = \frac{W_c \times V^2 \text{ tip}}{2g \times 550}$$

$$V_{tip} = \frac{2500}{60} \times \pi \times \frac{13.5}{12} = 147 \text{ fps}$$

$$W_c = \frac{910 \times .075}{60} = 1.14 \text{ lbs/sec}$$

$$\text{Ideal hp}_{chip} = \frac{1.14 \times 147^2}{64.4 \times 550} = 0.7$$

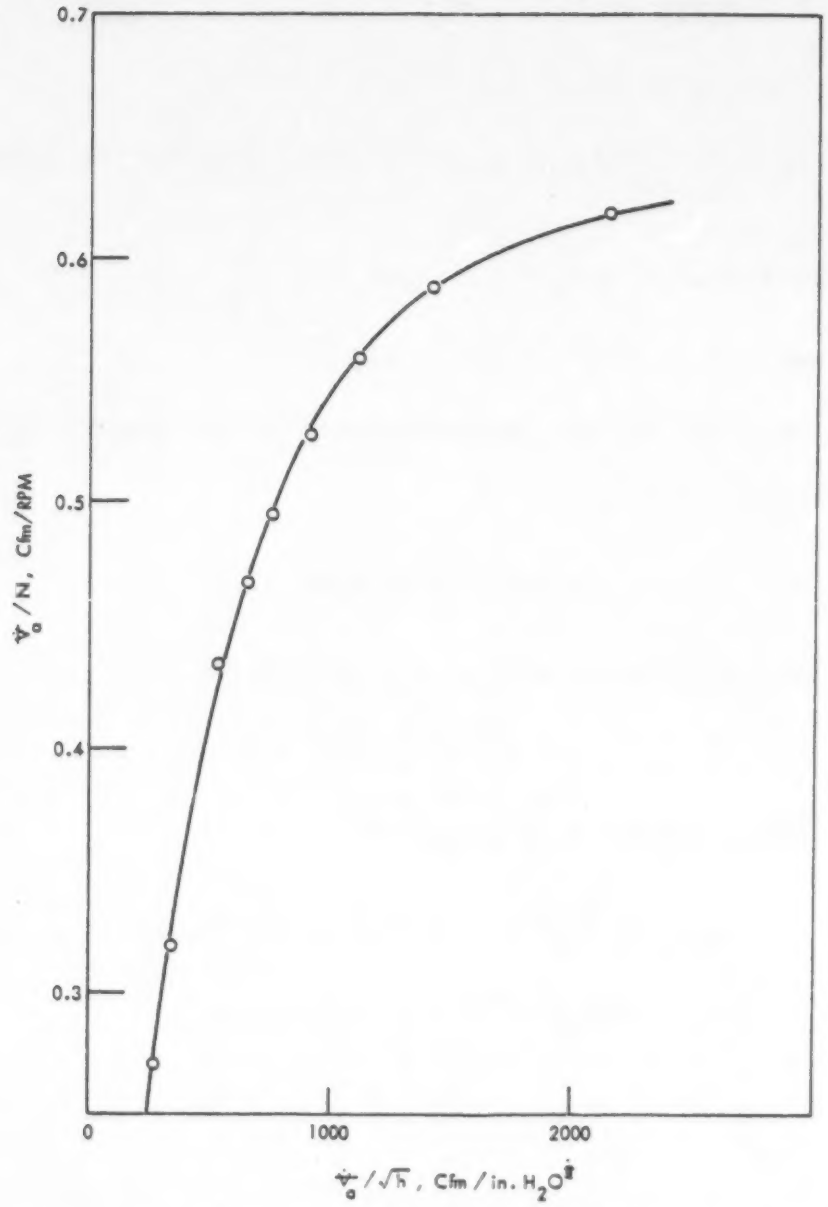

Figure A-1. 13¼" Dayton blower characteristic at standard conditions (0.075 lb./ft^3).

F_p (Ref. 1, p. 139) = 3 (Conservative Estimate)

h_p actual = 3 x 0.7 = 2.1

+ air hp

$\underline{\text{Required total hp}} = \frac{1.0}{3.1}$ at 2500 RPM

A 5.0 hp (at 3600 rpm) gasoline engine was selected to drive the blower through a 1:1 V-belt system. Thus, 3.47 hp is nominally available at 2500 rpm which allows a 12% margin for drive losses.

DEMONSTRATION TESTS

The sorbent characteristics (19 mm cubes with density range from 0.13 to 0.24 g/cc) are not sufficiently similar to the sorbents used in Reference 1 to allow complete confidence in the design method. Hence, a demonstration test series was performed to validate the system's performance and establish its characteristics and operational limitations as part of the design process.

The components identified in the preliminary design were assembled and instrumented at HYDRONAUTICS, Incorporated. Sorbent cubes (19 mm) having two different densities were used in the tests:

Type B at 0.156 g/cc.

Type G at 0.197 g/cc.

Measurements included the torque, T, and speed, n, of the engine; static head at the blower outlet, p_1; static head developed by the blower, SH, i.e., between the outlet and inlet; the dynamic head, $q = \frac{1}{2}\rho V_a^2$; and sorbent particle velocities. Independent variables in the test series were the sorbent type, sorbent flow rate (from 0 to 0.78 kg/sec), and various duct/nozzle configurations.

Blower Characteristics--

The normalized blower characteristics were obtained by running the system at several (engine) throttle settings and varying (throttling) the discharge airflow. The results are shown in Figure A-2 and compared with the manufacturer's values. The data for the ratio of static to dynamic head with no sorbent are self-consistent, but indicate that the measured values of static head (SH) are low compared with published values. Of course, the placement of the inlet and outlet static taps was arbitrary and inflow conditions were far from the ideal conditions normally used to establish blower curves.

The blower efficiency curve has some scatter which may be attributed to inaccuracies in the measurement of engine torque, T.

Sorbent Velocity--

The sorbent particle velocity through a transparent section of the transport duct was deduced from slow-motion pictures (400 frames/sec). The results are shown in Figures A-3 and A-4 for isolated particles (unloaded) and for randomly selected particles when loaded, respectively. The open symbols in Figure A-3 show the mean velocity of seven isolated particle cubes, V_c, at each of three air speeds, V_a = 14, 18 and 23.5 m/sec. The test at the lowest speed was repeated for both sorbent types. The closed symbols give the highest speed among the seven particles in each test run. The error bars on the open symbols indicate the standard deviation ($\pm\sigma$) of the measured particle velocity about the mean.

The symbols in Figure A-4 are similar, but approximately 25 particles among a population of several hundred were randomly selected to obtain the mean particle velocity during a test run with sorbent loading. The maximum particle velocity was obtained from inspection of the entire population.

The air velocity in the unloaded case was derived from the dynamic head measured by a pitot probe placed in the transport duct. The data in Figure A-3 show that a sorbent particle will occasionally approach the air velocity in the duct, but the mean velocity of isolated cubes is lower than the air velocity by a constant increment or slip velocity as shown by the dashed line through the data and parallel to the solid line for $V_c = V_a$. The slip velocity is nominally 8.5 m/sec for both sorbent types.

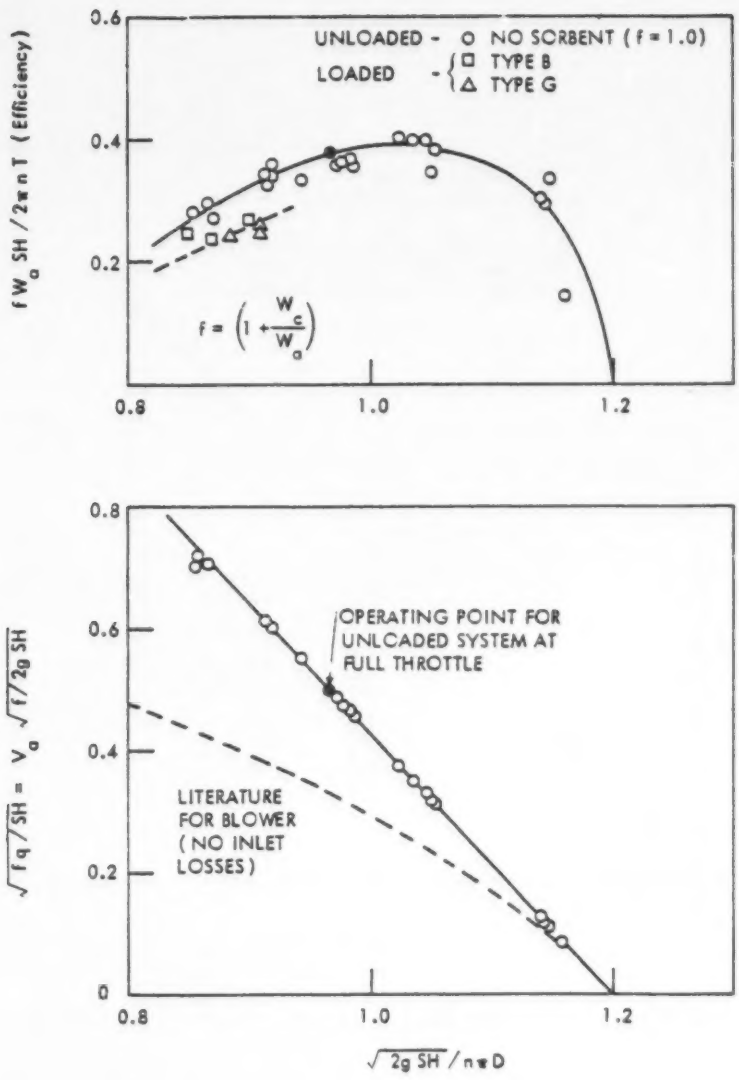
UNLOADED - O NO SORBENT (f = 1.0)
LOADED - □ TYPE B
△ TYPE G
f W_a SH / 2π n T (Efficiency)
f = (1 + W_c / W_a)
0.6
0.4
0.2
0.8
1.0
1.2
OPERATING POINT FOR UNLOADED SYSTEM AT FULL THROTTLE
LITERATURE FOR BLOWER (NO INLET LOSSES)
√f q / SH = V_a √f / 2g SH
√2g SH / nπD
0

Figure A-2. - Blower characteristic curves.

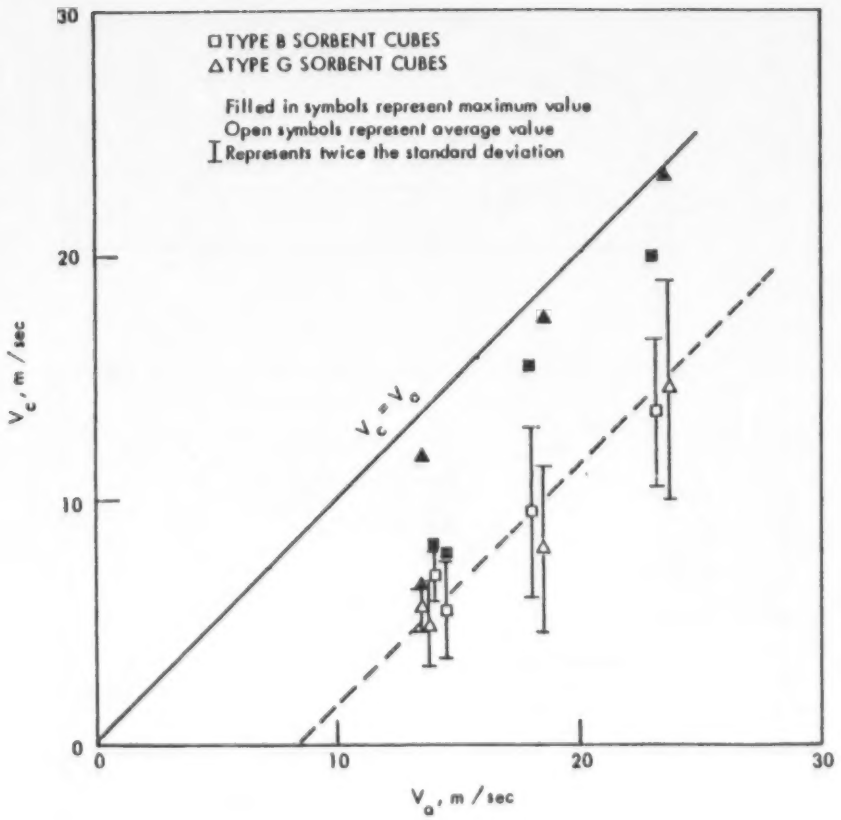

Figure A-3. - Velocity of single particles (unloaded).

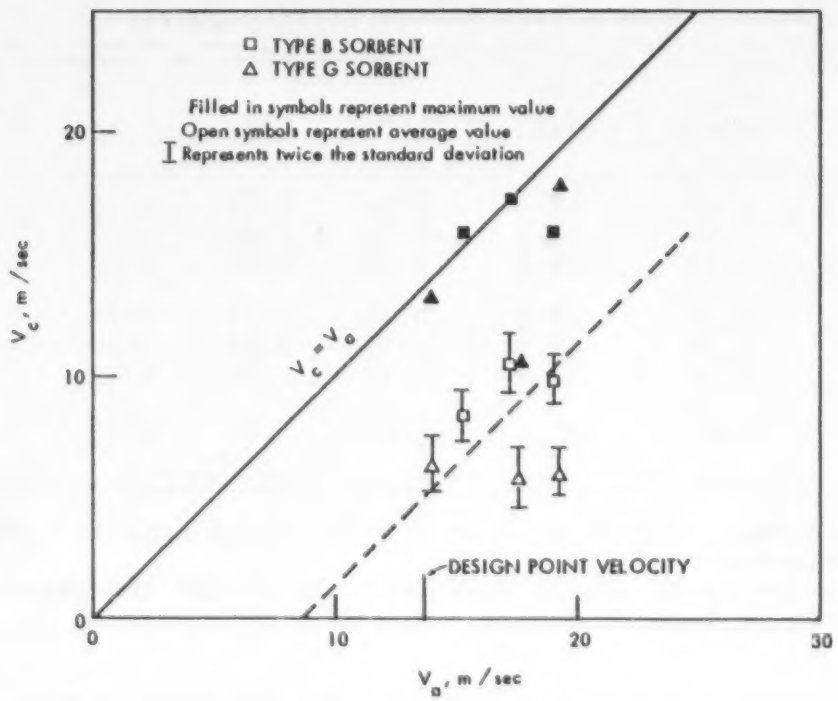

Figure A-4. - Particle Velocities (loaded, full throttle).

Loaded Air Velocity--

The air velocity in the loaded case was deduced from the blower characteristic curve (Figure A-2), because the pitot probe could interfere with the flow of sorbent particles and its operation would, in turn, be affected by the cubes. The computation was based on the assumption that the ratio of effective dynamic head, fq, to static head is a function only of the static head normalized by the blower speed, where $f = 1 + W_c/W_a$ and $q = V_a^2/2g$ (note, SH is in meters of air). The results are shown in the following table.

TABLE A-1. LOADED AIR VELOCITY
(Deduced from Blower Characteristic Curve)*

Sorbent Type	W_c Kg/sec	V_a m/sec	W_c/W_a	f	n, rps	Hp**
B	0.39	19.1	0.54	1.54	35.8	2.78
	0.52	17.2	0.80	1.80	36.7	2.85
	0.78	15.2	1.35	2.35	32.3	2.51
G	0.26	19.4	0.35	1.35	39.7	3.08
	0.39	17.6	0.58	1.58	36.5	2.83
	0.52	14.6	0.94	1.94	34.7	2.69
None	0.0	27	0.0	1.0	47.3	3.67

*Assumed that $\sqrt{fq/SH}$ vs $\sqrt{2g\ SH}/n\pi D$ is the same for loaded and unloaded condition.

**Engine torque is nearly constant ~6.8 ft-lbs (horsepower is given in English units).

The blower efficiency based on the measured static head and the combined weight of air and sorbent flow is seen in Figure A-2 to be reduced by a factor of about 0.8 relative to the unloaded (air only) case.

The deduced air velocities appear to be consistent with the measured maximum particle velocities in Figure A-4. The mean sorbent velocity seems nearly independent of the air velocity,

in the limited range of these tests, however; and the heavier Type G sorbent moved decidedly slower, V_c ~ 6 m/sec compared to ~10 m/sec for Type B.

System Losses--

The effects of the sorbent loading on the head losses are shown in Figure A-5, where p_1/q is the normalized head loss in the duct and nozzle and $(SH-p_1)/q$ represents the losses on the inlet side of the blower. Although there is considerable scatter in the data, the inlet losses are relatively independent of the loading factor, f. The duct and nozzle losses increase with increased sorbent loading, especially with the Type G foam. When these losses are normalized by the effective dynamic head, fq, the resulting loss coefficient is nearly constant for the Type G sorbent, but decreases with loading factor for Type B.

The higher losses for Type G may be caused by their greater density and/or their greater resiliency which seems to cause a noticeable increase in the number of collisions with the duct walls; hence, the lower mean velocities that were noted earlier. The nozzle contributes about 60 percent of p_1 for the unloaded system. Hence, the nozzle loss coefficient is about 0.8.

Limiting Factors--

For both types of sorbent the limiting factor for sorbent loading was the available torque of the 5-hp gasoline engine. The maximum sorbent loadings that could be condinuously maintained were:

Type B = 0.78 Kg/sec or 5.0 liter sec.

Type G = 0.52 Kg/sec or 2.6 liter/sec.

The maximum transport rate was not measurably affected by the nozzle or even small radius 180°-bends in the transport ducting. Greater rates could be sustained for short (~2-second) intervals if the mean loading rate was not increased.

The minimum air velocity for satisfactory sorbent transport was nominally 15 m/sec.

The mechanism by which the sorbent transport failed may be described as follows. As sorbent feed rate increased, the engine speed decreased (at nearly constant torque) until the

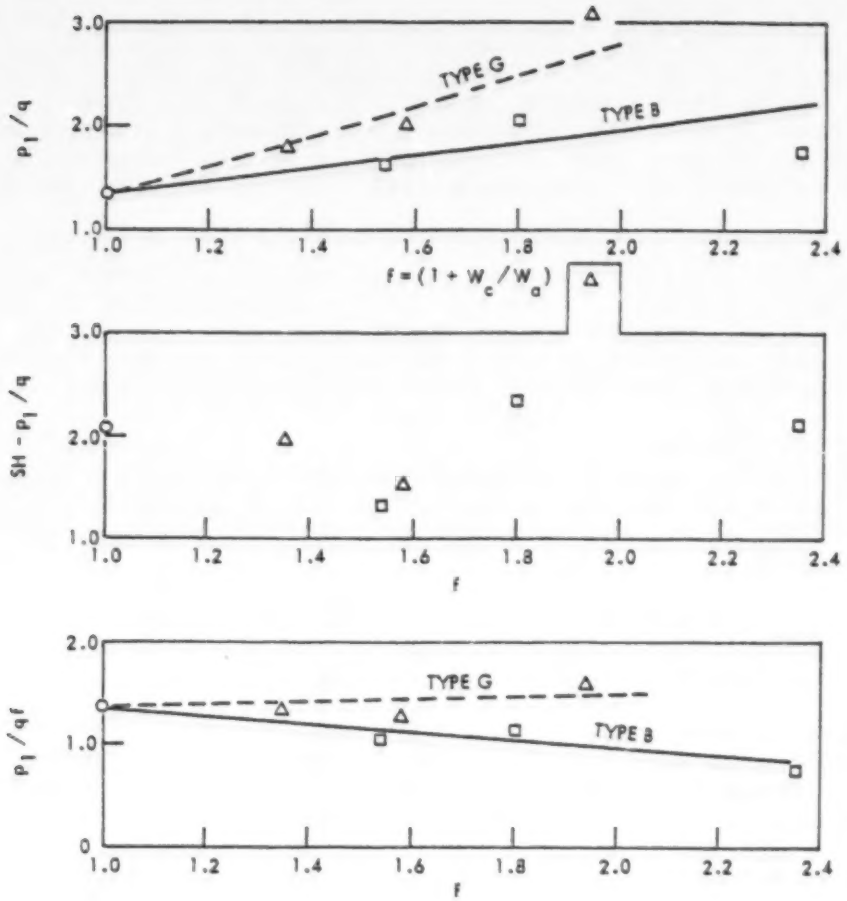

Figure A-5. - Pressure losses in the system as a function of the sorbent loading coefficient, f.

air velocity in the duct was insufficient to maintain sorbent transport. The duct would fill up and become clogged and/or the engine would stall. Sorbent lying in the blower, hopper, and/or duct was readily cleared when the engine was restarted except when the duct was fully clogged, i.e., a short section of duct was full from top to bottom so that the flow of air was completely shut off.

Final Design

The only major change to the preliminary design of the sorbent transport/broadcasting system arising from the demonstration tests was to substitute a 7-hp gasoline engine for the 5-hp drive. The design point performance, 0.52 Kg/sec, was achieved by the system as tested with Type G sorbent and exceeded by 50% with Type B sorbent. Since the only limiting factor in any of the tests was attributable to the available engine torque, we feel that the added weight (4.5 kg) to the system is justified by the expected increase in performance (up to 1.1 Kg/sec) capability. Estimated weight of the final system design follows.

Dayton No. 4C131 Blower plus hopper and duct flange.	39 kg	
7 hp 4-cycle Briggs and Stratton gasoline engine with vertical shaft.	15 kg	
Base for engine and blower.	23 kg	
Total Blower Assembly	77 kg	(170 lbs)
Nozzle.	4 kg	
7.3 meters of 8-in. dia. stove pipe and "flexflyte" hose	21 kg	
Total System.	102 kg	(225 lbs)

Reference:

1. Miller, E; Stephens, L.; and Ricklis, J. (January 1973.) Development and Preliminary Design of a Sorbent-Oil Recovery System. U. S. Environmental Protection Agency Report No. EPA-R2-73-166.